NASA/TM—2015–218935

Modular Extended-Stay HyperGravity Facility Design Concept

An Artificial-Gravity Space-Settlement Ground Analogue

Gregory A. Dorais, Ph.D.
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NASA STI Program ... in Profile

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Acknowledgments

This document was written while I served as the Chief Technologist and Deputy Program Manager for the NASA Space Technology Mission Directorate Small Spacecraft Technology Program. As Sir Isaac Newton so eloquently stated, "If I have seen further, it is by standing on the shoulders of giants." In this case, the two predominant giants on whose shoulders I attempted to stand on are Konstantin Tsiolkovsky and Wernher von Braun. They had the insight, conviction, and fortitude to lead the way in breaching the barrier that has confined life to the Earth and their works continue to point the way for those who aspire to go beyond Earth. I also gratefully recognize John Allmen, Mark Turner, and Catherine Dorais for their encouragement and their numerous comments on multiple drafts of this document making it clearer than it otherwise would have been, but I take responsibility for all the shortcomings that remain.

This report is available in electronic form at

http://www.sti.nasa.gov/ and http://ntrs.nasa.gov/

Table of Contents

Table of Figures

1.0 INTRODUCTION

1.1 Purpose

This document defines the design concept for a ground-based, extended-stay hypergravity facility as a precursor for space-based artificial-gravity facilities that extend the permanent presence of both human and non-human life beyond Earth in artificial-gravity settlements. Since the Earth's current human population is stressing the environment and the resources off-Earth are relatively unlimited, by as soon as 2040 more than one thousand people could be living in Earth-orbiting artificial-gravity habitats. Eventually, the majority of humanity may live in artificial-gravity habitats throughout this solar system as well as others, but little is known about the long-term (multi-generational) effects of artificial-gravity habitats on people, animals, and plants.

In order to extend life permanently beyond Earth, it would be useful to create an orbiting space facility that generates 1g as well as other gravity levels to rigorously address the numerous challenges of such an endeavor. Before doing so, developing a ground-based artificial-gravity facility is a reasonable next step. Just as the International Space Station is a microgravity research facility, at a small fraction of the cost and risk a ground-based artificial-gravity facility can begin to address a wide-variety of the artificial-gravity life-science questions and engineering challenges requiring long-term research to enable people, animals, and plants to live off-Earth indefinitely.

NASA has been interested in developing such a facility since at least 1969 (Larson, 1969) and scientists, such as Dr. Wernher von Braun were working on the concept decades earlier. In 1952 while von Braun was the Technical Director of the U.S. Army Ordnance Guided Missiles Development Group, he publicized the conceptual design of an orbiting space station that would rotate to produce "synthetic" gravity. The design he envisioned in that article was a 250' diameter wheel, constructed in Low-Earth orbit (LEO) out of modules, and is shown in Figure 1.

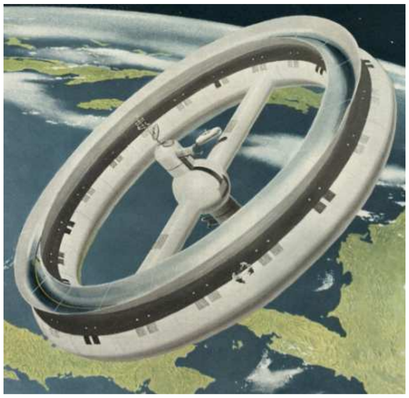


Figure 1: Wernher von Braun Space Station Design (Bonestell) in (von Braun, 1952)

In this article, von Braun describes this space station producing 1g by rotating with a rotational period of 12.3 seconds (4.9 RPM) and producing 1/3g by rotating with a rotational period of 22 seconds (2.7 RPM) (von Braun, 1952).

At the request of the NASA Administrator to make recommendations for astronaut health for long-duration missions, the National Academies Institute of Medicine committee recommended for NASA to focus on giving, “increased priority to understanding, mitigating, and communicating to the public the health risks of long-duration missions beyond Earth orbit” and “using more extensively analog environments that already exist and that have yet to be developed;” (Committee on Creating a Vision for Space Medicine During Travel Beyond Earth Orbit, Board on Health Sciences Policy, 2001). More recently, the International Academy of Astronautics Study Group on artificial gravity recommended that, “the most efficient means of developing an effective flight artificial gravity countermeasure is by appropriate and timely use of ground facilities” (International Academy of Astronautics, 2009). The report by The National Academies National Research Council (NRC) Aeronautics and Space Engineering Board of their review of the NASA Space Technology Roadmap states, “The panel identified Artificial Gravity Evaluation/Implementation as a game-changing capability that would greatly mitigate many adverse health effects that would otherwise occur during long-duration habitation in transit (or Earth orbit).” (NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space, 2012, p. 195).

The ground-based artificial-gravity facility design concept described herein is the extensible, modular, Extended-Stay HyperGravity Facility (ESHGF). The ESHGF produces an adjustable, hypergravity-level (gravity exceeding 1g) environment in a 150m radius rotating facility for people to work and live in along with animals and plants for long-term periods. The design is extensible so that it can be incrementally implemented so that small-scale operations can be realized within a relatively short schedule and low budget. The ESHGF capabilities and capacities can be incrementally increased as demand and budgets permit.

1.2 Benefits

The ESHGF is expected to yield several benefits:

- Validate artificial-gravity facilities on Earth as a precursor for their development off-Earth. The greater the rotation rate and shorter the centrifuge radius required for humans to be safe and comfortable with over long-periods, the smaller the mass and cost for an artificial-gravity space facility. The report, “Safe Passage: Astronaut Care for Exploration Missions” (Committee on Creating a Vision for Space Medicine During Travel Beyond Earth Orbit, Board on Health Sciences Policy, 2001) extensively documents many areas in which knowledge is insufficient regarding the health of astronauts on long-duration missions. Even less is known regarding the effects of various and changing gravity levels on the health of humans living off-Earth indefinitely including child development.

  An ESHGF can be used as an analogue for future artificial-gravity facilities located on-orbit, on the surface or in tunnels in the Moon, Mars, Phobos, Deimos, and asteroids, as well as to research what life might be like under such conditions. The resulting science would be beneficial in designing future spacecraft and space facilities requiring artificial gravity. Doing so can enable the permanent residence of humans off Earth in rotating facilities such that the environment of these settlements are engineered to be Earth-like by providing artificial gravity.

- Characterize the effects and risks of long-term and periodic exposure to various hypergravity levels on humans, animals, and plants in a closed, engineered environment. With renewed interest in human missions to Mars (NASA, 2015), any credible attempt will need to provide some type of gravity augmentation due to the extended duration of such missions. To date, only a few people have lived off-Earth for more than a year and the extended time in a microgravity environment caused significant detrimental effects, e.g., muscle loss, cardiovascular deconditioning, and a reduction in bone density. Little is known of the long-term (multi-year and multi-generational) effects for humans, plants, and animals living in a gravity environment of other than 1g. An overview of the effects of microgravity on humans and artificial gravity research is presented in Artificial Gravity (Clément & Bukley, 2007).

- Characterize the long-term effects of living in rotating environments with radii significantly greater than 10m. Human centrifuges have been tested with radii <10m for short periods, but the short-radius rotational effect is too uncomfortable for humans at more than a few RPM even for short periods, e.g., motion sickness, and the cockpits were too small for long-duration tests. The "Coriolis effect" is experienced when moving within a rotating reference frame, such as a vehicle or centrifuge, and is associated with vestibular disturbances resulting in motion sickness and disorientation. The physiological effects of Coriolis accelerations with respect to artificial gravity systems are of particular research interest (Matsnev, 1996). Negative Coriolis effects are mitigated by constraining head movement and body translation in a centrifuge, but it is undesirable to constrain either for humans in a long-term artificial-gravity facility.

  In addition to the Coriolis effect, the gravity gradient of a centrifuge can be a significant issue. A person standing in a centrifuge with a 8m diameter and subject to centripetal acceleration that generates 1g at the feet will only experience approximately 0.5g at the head (excluding Earth gravity). Since the brain contains the vestibular system used to sense gravity and accelerations, such a sharp gravity gradient is disorienting when the person moves, among other things. This gradient decreases as the centrifuge diameter increases and is negligible in a centrifuge with a diameter of 300m that this design concept describes.

- Provide flight crew training and physical therapy to mitigate the effects of prolonged exposure to microgravity environments. Living in a microgravity is known to cause a variety of adverse effects. By living in a hypergravity environment before and/or after prolonged exposure to a microgravity environment, the negative effects may be mitigated and the rehabilitation may be accelerated for space flight crew (Davis-Street & Paloski, 2007), (Yang, Baker, Graf, Larson, & Caiozzo, 2007).

- Provide physical therapy to improve human and animal health and capabilities. Long-term living in a hypergravity environment can increase muscle strength and bone density as well as strengthen organs and improve resistance to loss of consciousness under high-g conditions. Preliminary studies of the effects of prolonged hypergravity on rats, up to 4.7g for up to 1 year, resulted in no deleterious effects and discovering significant physiological changes to the rats, such as significant increases in organ and bone mass with little change in overall weight compared to the control rats (Oyama & Platt, 1965). Additional research is required to determine the long-term effects of hypergravity on larger mammals as well as the

longer-term, multi-generational consequences of hypergravity. Once validated for prolonged use by humans, this facility could be used for individuals benefiting from extraordinary strength, e.g., athletes, and select military personnel. It also could be used for physical therapy for patients unable to exercise, e.g., subject to extended bed rest, and for elderly individuals to mitigate muscle loss and bone loss (e.g., osteoporosis). There is also evidence that hypergravity may have therapeutic applications involving cellular development (Genchi, et al., 2015).

- Provide health, recreational, and educational facilities for short-term visitors to engage the public in NASA's effort to extend life beyond Earth. Among other things, this would allow the public to interact with NASA researchers and their subjects in a stimulating environment.

- Validate the human use of a wide-variety of systems that were engineered and tested for use on Earth at 1g, e.g., shower, toilet, blender, washing machine, refrigerator, since their performance can vary significantly at different gravity levels. Enabling the development of 1g space facilities significantly reduces or entirely eliminates the cost and risk of reengineering the wide variety of objects and systems needed by space settlements.

- Provide a mobile facility capable of housing a scalable number of people, from none to thousands.

- Provide a wide variety of habitats for plants and animals ranging from desert to oceanic.

Additional less tangible benefits can be expected from building a realistic space-settlement analogue and permitting the general public to tour it, such as the inspiration that is derived from leading the way for the permanent migration of life beyond Earth that includes thousands of people within the lifetimes of most of us.

1.3 Background

The ESHGF is essentially the merger of two technologies: centrifuges and trains, in which an extremely long-arm centrifuge is created using vehicles similar to tilting trains.

1.3.1 Centrifuges

Human centrifuges have been used to generate hypergravity for centuries. Erasmus Darwin recounted experiments in which the human subject was placed on a rotating corn-mill stone, which was accelerated to an RPM that mechanically induce “sleep” (Darwin, 1809). Centrifuges were used in psychiatric wards to treat patients in the early 1800s (Harsch, 2006).

Currently, an 18m radius centrifuge operates at the Yuri Gagarin Research & Test Cosmonaut Training Center that is capable of generating up to 8g, has three interchangeable cabins mounted at the end of the arm, and is used for space crew training (Gararin Cosmonaut Training Center, 2015). As shown in Figure 2, a 29’ radius 20g centrifuge (human-rated for 12.5g) operates at the NASA Ames Research Center and has exposed human subjects to hypergravity for durations up to 22-hours (NASA ARC, 2015). Both centrifuges have relatively small cabin sizes and the occupants generally are intended to remain stationary within the cabins during operation.

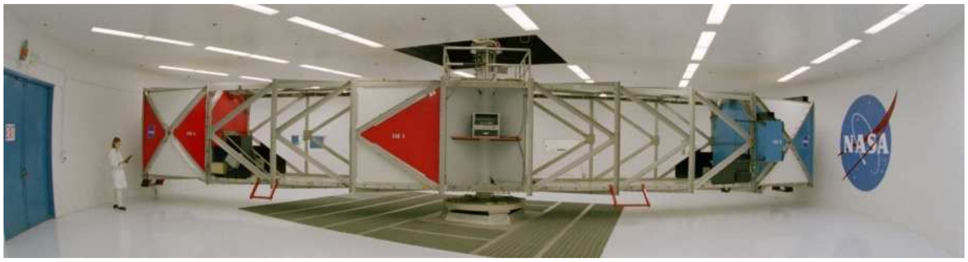


Figure 2: NASA Ames Research Center 20g Centrifuge (NASA ARC, 2015)

Orbiting Centrifuges

In 1895, Konstantin Tsiolkovsky, a pioneer of astronautics, wrote "Dreams of Earth and Sky," in which he imagined generating artificial gravity in space by means of trains running in circles (Tsiolkovsky K. , 1895/1979), (Andrews, 2009). Later in "Investigation of World Spaces by Reactive Vehicles (1911-1912)," he noted that the further a human subject is from the axis of a centrifuge the better. Tsiolkovsky also experimented with centrifuges on animals and proposed that a train on a tilted, circular track could be used to generate artificial gravity over extended periods for research (Tsiolkovsky K. E., 1911-1912/2004, pp. 118-121). However, there is no record that such a train was ever designed or built.

Starting in the 1950s, humans were tested in a centrifuge with a 50' arm, capable of generating close to 50g's, at the Naval Air Development Center in Johnsville, PA. In 1958, this facility was used to test X-15 pilots and later was used for astronaut testing for the NASA Mercury, Gemini, and Apollo space programs (Hoey, 2010, pp. 398-400). In 1959, the Army Ballistic Missile Agency proposed a human "Space Flight Simulator" that consisted of a 500'-radius superelevated circular track, a 4-person 24' jet-powered sled, a transition track, and a 3622' vertical track that the sled would ascend and launch into a sub-orbital trajectory after reaching a sufficient velocity by traveling on the circular track (Gerathewohl, 1961).

In the 1975 NASA study, "Space Settlements: A Design Study," an orbiting space settlement capable of supporting a population of ten thousand is described in detail. The orbiting space settlement envisioned in this study is shown in Figure 3.

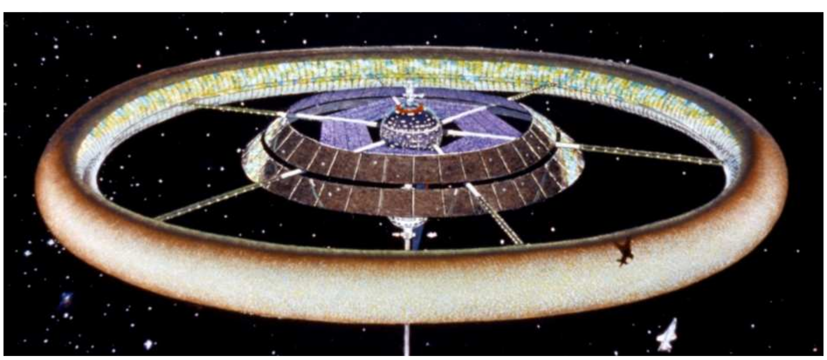


Figure 3: Orbital Space Settlement (NASA, 1977)

In this design, the 1790m diameter space station wheel rotates at 1 RPM inside a non-rotating ring shield to produce 1g at the wheel rim bottom floor (Space Settlements: A Design Study,

1977). The wheel rim modules can be viewed as train cars running on a circular track in which the track is the ring shield.

Thomas W. Hall's doctoral dissertation, "The Architecture of Artificial-Gravity Environments for Long-Duration Space Habitation," describes several design considerations with regard to designing facilities for long-term occupation that rely on spin-induced centripetal acceleration to generate artificial gravity (Hall, 1994).

A long-duration, large-radius "Human Hypergravity Habitat" was proposed (van Loon J. J., 2009), (van Loon & Wuyts, 2009), (van Loon J. J., 2012). The concept is essentially a train on a circular track designed to generate a specific, long-duration hypergravity level for humans. The ESA Large Radius Human Centrifuge Topical Team recommended a track diameter of 150m with a maximum design load of 2g's. Initial tests for long-term hypergravity exposure should be in the range of 1.4 - 1.5g's and then incrementally increased (van Loon & Wuyts, 2009).

1.3.2 Trains

An ESHGF can be implemented using readily available wheeled-train technologies. Trains have been used for over two centuries for reliable transport and are operational around the world. They remain a dominant, low-cost means of transportation.

Richard Trevithick is credited with building the first steam-powered train. It was based on a portable steam engine patented by Trevithick and Andrew Vivian in 1802 (Dickinson & Titley, 1934, pp. 269-278), and ran 9 miles at nearly 5 miles per hour carrying 10 tons of iron, 5 wagons, and 70 men in South Wales on 2/21/1804; heralding a new age of transportation (Dickinson & Titley, 1934, pp. 63-71) (Amgueddfa Cymru — National Museum Wales, 2008).

Tilting Trains

Trains with tilting cabins to compensate for track cant as well as centripetal acceleration on curves began development in the mid-1930s (Van Dorn & Beemer, 1940), (Life Magazine, 1940). These first tilting cabins were mounted on their rail car chassis with pivot points above their cabin centers of gravity and passively pivoted due to gravity and inertia. During the same period, actively-controlled train cabins were designed to tilt hydraulically (Schoepf & Ritchie, 1937), (Schoepf & Ritchie, 1937a). Although actively controlled tilting train cabins were not put into operation until decades later, cabin tilting technology is now considered mature. As of 2007, over 5,000 tilting-cabin train cars have been produced worldwide by several suppliers (Persson, 2007), (Khedkar, Kasav, Jadhav, Katkade, & Gunjal, 2015).

Roller Coasters

Although tilting trains can compensate for some centripetal acceleration and track cant, a different technology was developed for trains designed to operate with high levels of centripetal acceleration and steep track banks, which has been primarily used for roller coasters. The first modern roller coaster using tubular steel rails was developed by Karl Bacon and Edgar Morgan at Arrow Development for Walt Disney Productions. Their patent for this invention states the purpose was to, "carry passengers at high speeds with absolute safety over a path that includes very sharp and highly banked curves, such as are found in a bobsled course." (Bacon & Morgan, 1965). This technology was first instantiated in the Matterhorn Bobsled roller coaster at Disneyland, which began operating in 1959. Karl Bacon also patented the first "corkscrew" roller

coaster using tubular steel rails, which began operating at the Knott's Berry Farm amusement park in 1975, (Bacon, 1975), (Reynolds, 1999). Variations of their looping tubular steel rail roller coasters continue to be used worldwide with the fastest commercial roller coaster in 2015 being the Formula Rosso at Ferrari World Abu Dhabi, United Arab Emirates, which reaches 240km/h (149 mph) on a 2.07km track (Ferrari World Abu Dhabi, 2015).

Locomotion

Currently, nearly all trains use rotating electric motors in the cars or in the tracks to provide the torque required to rotate the wheels to move the trains. The electric motors in the cars are called electric traction motors and usually get their power from either diesel generators also located in the cars or from electric lines that run along the track or overhead. On some trains, only cars dedicated for locomotion (locomotives) have electric traction motors. An example of an electric locomotive currently being used is the Amtrak Cities Sprinter ACS-64. ACS-64s were adapted for service in the United States for speeds up to 201 km/h (125 mph) and are being used on the Amtrak North East Corridor between Boston and Washington D.C. (Siemens AG, 2015). However, on some trains each car has one or more electric traction motors to distribute the force required to move the trains providing redundancy and scalability. For some trains, such as many roller coasters, electric motors are attached on or nearby the track and used to propel the train, at least to a just beyond a high point after which gravity provides the required acceleration.

Linear motors are becoming more popular for use on trains. Unlike traditional electric motors in which that rotor rotates inside a stator to produce a torque used to turn wheels to produce a linear force, a linear motor in effect flattens the rotor and stator and directly produces a linear force without any moving parts. Linear motor are particularly attractive for magnetically levitated trains in which part of the motor is attached to the bottom and/or sides of the train and the other half is attached to the track (Hellinger & Mnich, Nov. 2009).

Magnetic Levitation

Ideally, an ESHGF would use superconductor magnetic levitation, which would provide a smooth, quiet, low friction, low-maintenance, and low energy-cost motion. The first patent for a linear induction motor for driving trains was granted to Alfred Zehden in 1905 (Zehden, 1905) followed by a patent granted to Emile Bachelet for a magnetic levitation transportation apparatus (Bachelet, 1912). In 1969, a patent for a Maglev train that uses superconducting magnets was granted to James Powell and Gordon Danby (Powell & Danby, Patent #: US003470828, 1969). Subsequently, with an operational speed of 430 km/h (267 mph) (without superconducting magnets), 464- seat Maglev trains in Shanghai began operations in 2003 (Antlauf, Bernardeau, & Coates, 2004), (The Shanghai Maglev Train, 2015). The Central Japan Railway is developing a superconducting maglev train (Central Japan Railway, 2014). On April 21, 2015 on the Yamanashi Maglev Line, an 18.4km test track, the L0 Series A07 superconducting maglev train ran at 603 km/h (375 mph) (Guinness World Records, 2015). Although the high-speeds of superconducting maglev trains are not required by an ESHGF, the other benefits mentioned above are significant.

Another magnetic levitation alternative for consideration is based on the Inductrack developed at the Lawrence Livermore National Laboratory. Unlike the above technologies, which use electromagnets for levitation, the Inductrack, patented by Richard Post (Post, 1998), uses Halbach arrays of permanent magnets for levitation (Post & Ryutov, 2000). This research was

sponsored in part by NASA to demonstrate the feasibility of using the Inductrack to accelerate a launch vehicle model at 10g to Mach 0.4.

Taking the next technological step in high-speed magnetic levitation, the "StarTram" concept has been proposed as a low-cost means to put cargo in orbit using superconducting magnetic levitation and linear motors (Powell J. R., Maise, Paniagua, & Rather, 2001), (Powell, Maise, & Pellegrino, 2013). For off-Earth space settlements requiring thousands of modules, the development of this type of infrastructure is worth further consideration. Once demonstrated on Earth, it could also be used on the Moon, which requires 1/6th the escape velocity and doesn't have an atmosphere that would significantly decelerate a launched payload, with or without passengers. This approach will be of extraordinary value in any significant effort to launch people and cargo from the Moon. Since no propellant is required, propellant won't have to be brought all the way from the Earth and safely landed on the Moon (or mined and processed from its polar craters).

2.0 DESIGN CONCEPT

Leveraging the above centrifuge and train technologies, the following design concept describes a modular ESHGF that can be initially implemented to support a few people, but can be incrementally extended as needed to reach a full-scale space settlement. This section begins with a brief system overview followed by a description of each subsystem. Hypergravity implications are discussed in section 2.6, including its effect on system sizing. This is followed by a description of ESHGF stability considerations, modularity, system capacity, and extensibility.

2.1 System Overview

The ESHGF system consists of the HyperGravity Vehicle, Vehicle Track, Transfer Vehicle (optional), and Depot subsystems as shown in Figure 4, which interact as depicted in Figure 5.

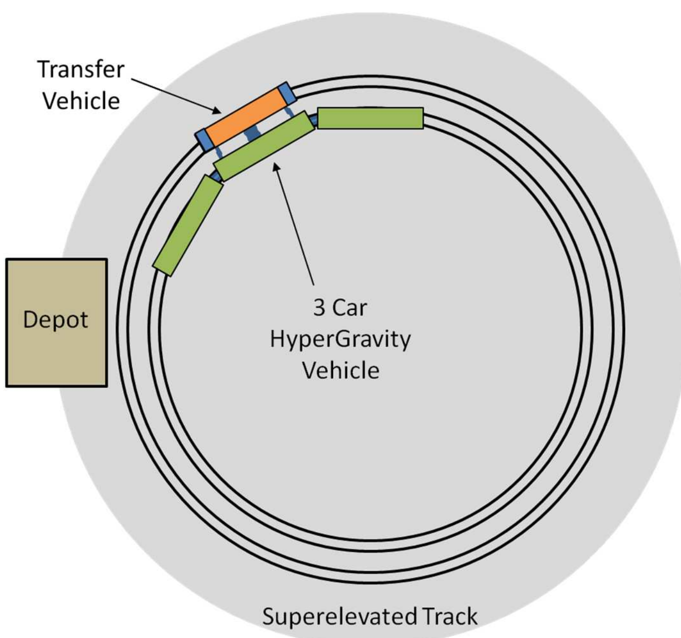


Figure 4: ESHGV System Top View depicted in a 3-car HGV configuration

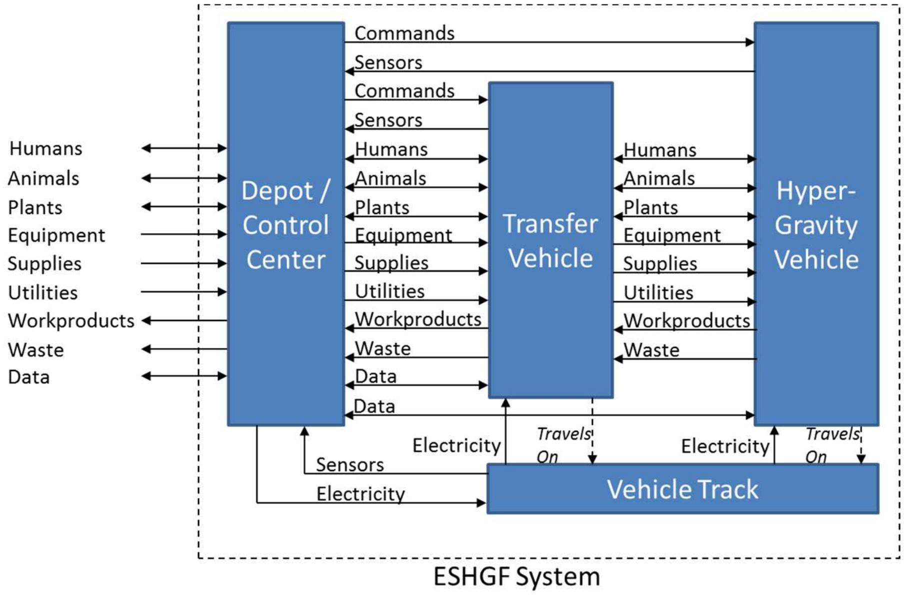


Figure 5: System Overview

Each of these subsystem are discussed further in the following subsections.

2.2 HyperGravity Vehicle Subsystem Overview

The HyperGravity Vehicle (HGV) subsystem is an electric train consisting of a sequence of connected cars running on a track. The top view of this subsystem is shown in Figure 4 and its elements and their interactions are depicted in Figure 6. People will be able to move between cars as they can onboard a typical train.

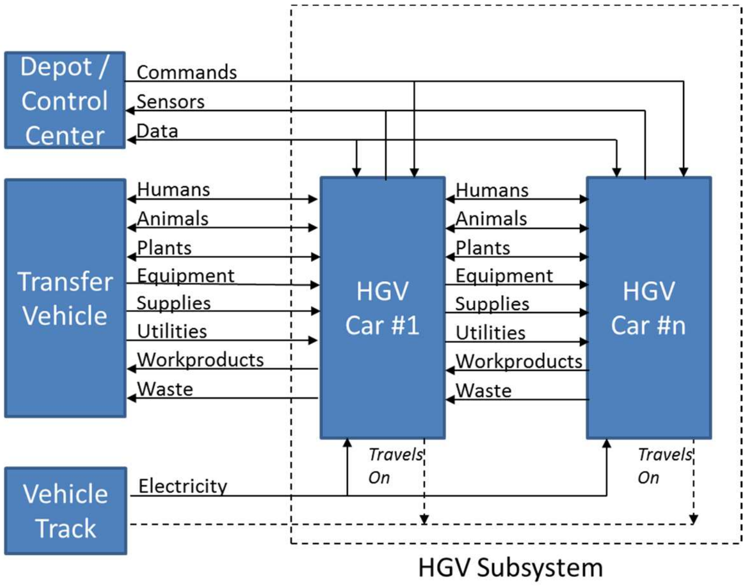


Figure 6: HGV Subsystem Overview

The general design is for all HGV Cars (HGVC)s to be the same size, but custom-size cars can be accommodated.

The interior of each car is expected to be customized to meet the needs of its occupants and manager. Car types are expected to include at a minimum living quarters and workspace. Other car types may include dining facilities, farms, aquariums, pools, arboretums, botanic gardens, factories, gyms, sports center, markets, meeting rooms, etc.

The three major elements of each HGVC: Cabin, Chassis, and Cabin Tilt Mechanism, are depicted in Figure 7 and Figure 8.

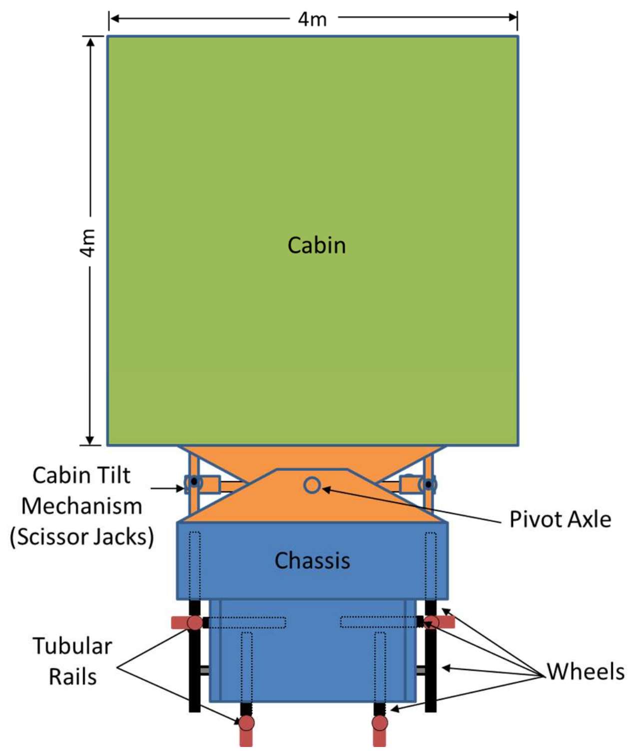


Figure 7: HGVC Front View (same as Rear View)

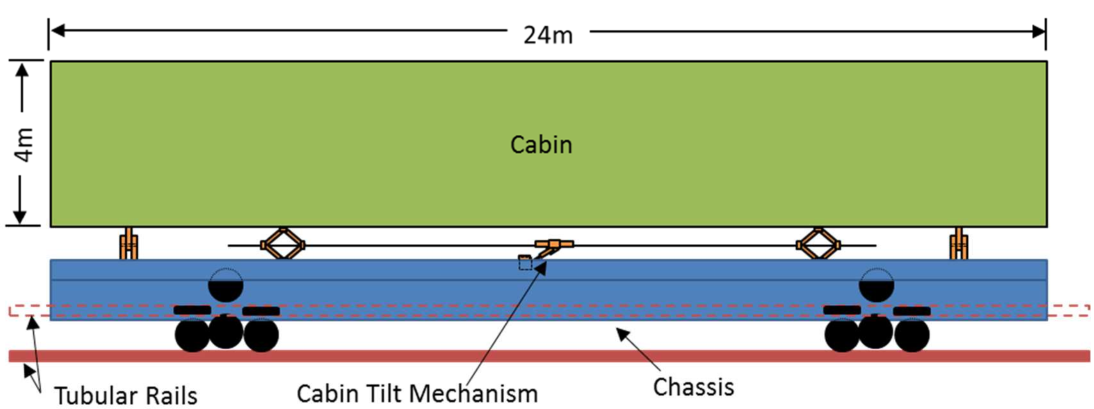


Figure 8: HGVC Side View (the same for both sides)

An HGVC with a 24 x 4 x 4m cabin on a 300m diameter 30° superelevated (banked) track with an additional Cabin Pivot Angle of 30° is shown in perspective in Figure 9.

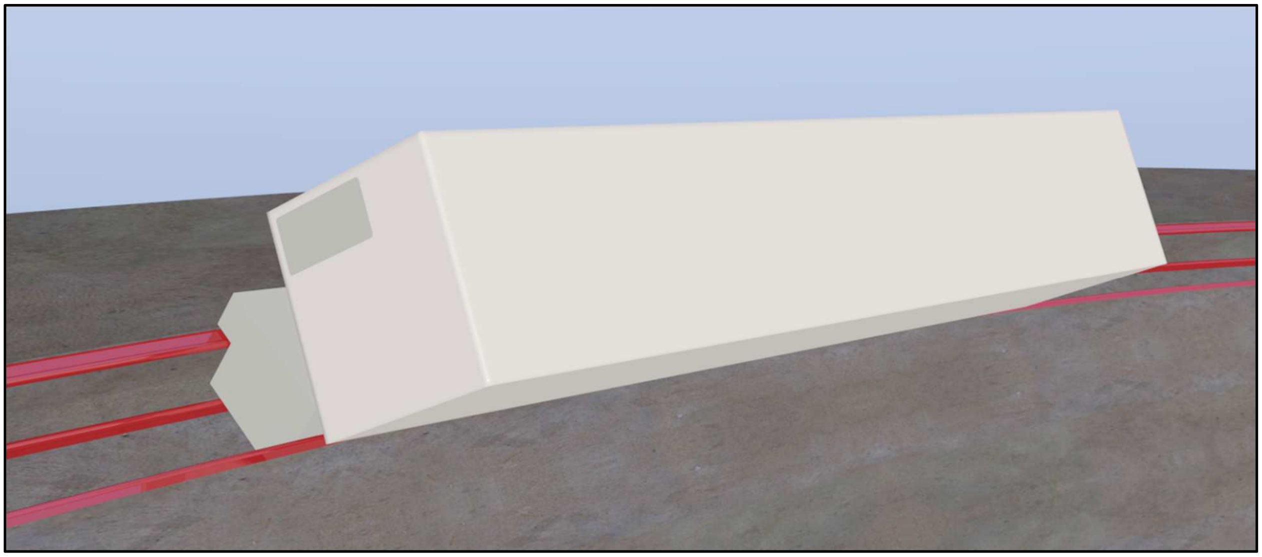


Figure 9: Single Cabin HGVC Perspective View

As per the third highlighted row in Table 1: Hypergravity Level Examples, to be discussed in section 2.6.1, the depicted is operating on the track at 3.2 RPM and generating 1.97g. At a lower RPM, the Cabin Pivot Angle would be less with a corresponding lower hypergravity level. HGCV stability design considerations to compensate for such a steeply superelevated track and HGVCs with high pivot angles are also discussed.

2.2.1 HGVC Chassis Subsystem Overview

The chassis is similar to a flatbed train car. It basically consists of a frame resting on two train wheel trucks, powered by electric traction motors, which run on a tubular rail track (see Figure 13). Variations of the chassis include those without motors requiring another car to provide locomotion. Ideally, the chassis would be magnetically levitated (maglev) to operate efficiently at high speeds as well as to reduce maintenance, friction, noise, and vibration, but it is not necessary and the additional costs and development delays may not be justified.

2.2.2 HGVC Cabin Subsystem Overview

The nominal Cabin sizes are 4m wide, 4m high, and either 12m or 24m long. These sizes were selected due to their similarity to train car sizes and their feasibility as analogues for off-Earth use. A space-rated version of this cabin could be accommodated as a payload on a heavy-lift launch vehicle for use on orbit, in the Moon, in Mars, in the Mars' moons. and in asteroids. By taking into account space-rated cabin requirements into consideration, the ESHGF can be used as an analogue for such modular artificial-gravity space facilities and validating their requirements.

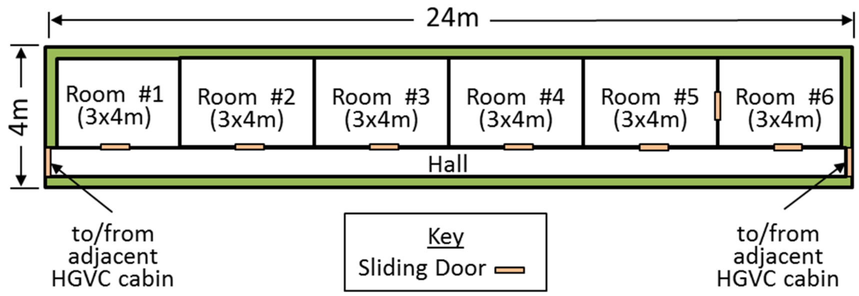


Figure 10: HGVC 6-room Cabin Floor Plan Example (Top View)

Each cabin has a hall connected to the adjacent Car cabin(s) for people and cargo to travel the length of the HGV as shown in Figure 10. This figure depicts a 6-room floor plan. However, the floor plans are flexible because internal cabin walls are not load bearing and may be moved.

2.2.3 HGVC Tilt Mechanism Subsystem Overview

A special feature of each HGVC is its capability to control the tilt of its cabin so that it is relatively level with respect to its hypergravity vector. The HGCV tilt mechanism subsystem enables this capability by actively controlling the tilt of the cabin with respect to the chassis depending on the velocity of the HGVC. Views of the HGVC Cabin Tilt Mechanism Subsystem are shown in Figure 11and the subsystem elements are their interactions are depicted in Figure 12.

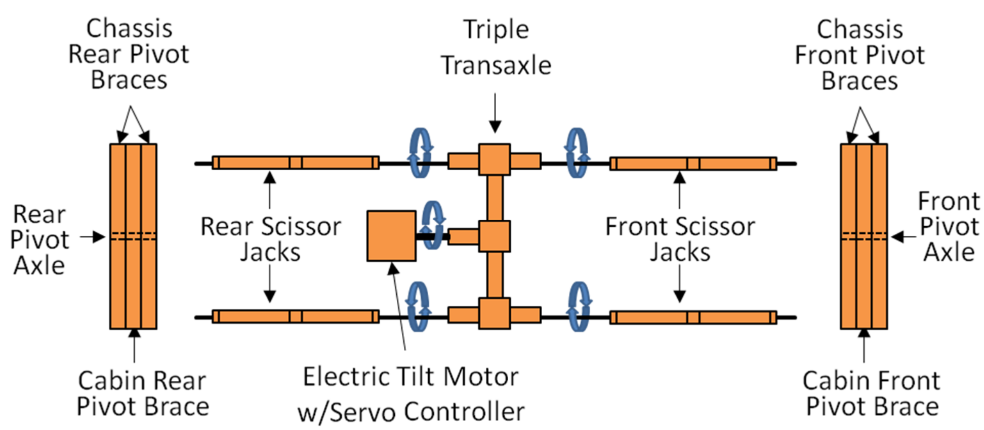


Figure 11: HGVC Tilt Mechanism Subsystem Top View (attached between chassis and cabin on each HGVC; blue arrows show rotations when pivoting to the right)

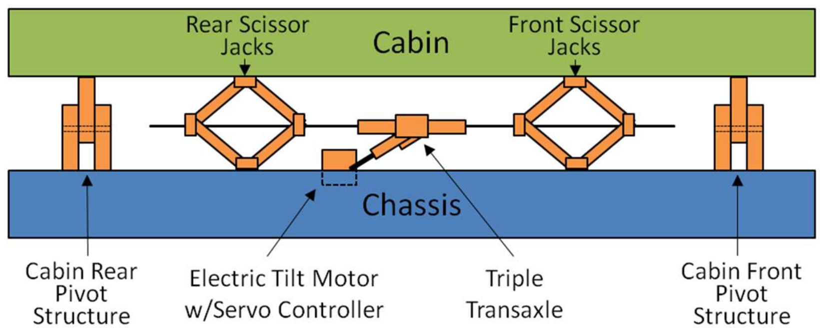


Figure 12: HGVC Cabin Tilt Mechanism Subsystem Side View

As shown in Figure 11 and Figure 12, as well as integrated in the HGVC in Figure 7 and Figure 8, the HGVC Cabin Tilt Mechanism attaches the HGVC Cabin and Chassis by means of two pivot structures and four scissor jacks. The scissor jacks are used to change the tilt of the cabin with respect to the chassis. A triple transaxle is used to transfer the input torque from the electric tilt servo motor to the four threaded rods of the scissor jacks. The triple transaxle outputs torques such that as the left jacks are raised, the right jacks are simultaneously lowered as shown in Figure 11. The electric tilt motor and its servo controller precisely control tilting the cabin to the commanded angle. The commanded angle is a function of the HGV velocity and the track (chassis) superelevation angle defined by Equation 3 discussed in 2.6.1

The design can accommodate additional jacks if needed and other types of cabin tilt mechanisms can be used instead, e.g., hydraulic jacks, but scissor jacks have the advantage of a highly controlled relationship between the jack height and tilt degree as well as lower maintenance requirements. A design alternative for the HGV velocity input to the servo controller is an inclinometer-signal input that the servo controller zeros by tilting the cabin.

2.2.4 HGVC Chassis Truck Subsystem Overview

The cabin(s) and its tilt mechanism rest on the chassis, which is used to move the car on the track discussed in section 2.3. The chassis consists of a frame attached to two electric-traction motor trucks. Each truck rides on the track and can passively rotate with respect to the chassis in order to stay centered on tracks. Although truck wheels may also passively rotate in response to another car pushing or pulling the chassis, in this design each truck is powered by electric motors to increase the locomotive traction and provide redundancy. The trucks are shown in the HGVC chassis bottom view in Figure 13.

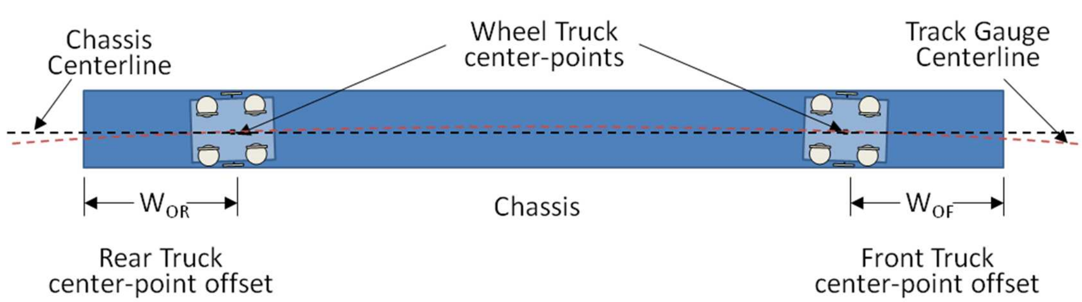


Figure 13: HGVC Chassis Bottom View

The two truck center-points on the chassis are the only two points on the chassis lengthwise centerline that are exactly the track radius distance (measured from the track circle center to the upper track gauge centerline – see Figure 30). The equal front and rear truck offsets (W_{OF} = W_{OR}) are also depicted in the figure. These metrics are significant with respect to hypergravity variations to be discussed in section 2.6.

2.2.5 HGVC Stability Design Considerations

The primary HGVC stability issue that must be addressed is atypical for trains and is due to the high side loads, and in some cases negative loads, on the HGVC wheels and tracks which could lead to an HGVC derailing and tipping over if not engineered properly. These loads are due to the steep track superelevation angle (30°), the tight turn radius (150m), the high speeds (112 mph), the pivoting cabins (+-30°), the shifting cargo and passengers, and the high cabin surface area subject to winds. In this design, the risk of derailment is mitigated by the HGVC chassis wheel truck horizontal and vertical side wheels that ride on three sides of the tubular-track side rails as shown in Figure 7, Figure 8, and Figure 9.

2.2.6 Inter-HGVC Connectivity

Initial HGV testing can be accomplished with a single HGVC. This design concept supports a multiple, connected HGVs that operate on the same track. These connections may be accomplished by extending the HGVC chassis and using train chassis couplers and the same way that most train cars are connected, but other methods may perform better. Standard train chassis couplers do not take advantage of the fact that the HGV runs on a superelevated, level track with a constant radius. Depending on the precision of the track, the HGVCs may be connected by a variety of other methods that provide additional strength, rigidity, and vibration damping. The details of how the HGVCs are connected require further study and are beyond the scope of this document.

In addition to the chassis connector, HGVs with multiple HGVCs also require flexible vestibules that provide a passageway between cabins on connected HGVCs similar to those between passenger train cars, but in this case the vestibules tilt with the cabins so the vestibule floor also is effectively level regardless of the HGV velocity. These vestibules are dependent on the HGVCs coupling design and further details are also beyond the scope of this document.

2.3 Vehicle Track Subsystem Overview

The Vehicle Track subsystem is the pathway for the HGV and Transfer Vehicle and provides electricity to both subsystems. Both tracks are superelevated and circular as depicted in Figure 14. Side views of the superelevated track are shown in Figure 16 and Figure 18. As depicted in both figures, a shell may be used to cover the track, HGV, and Transfer Vehicle to protect them from the weather and provide security.

Each track has four tubular rails to carry the load and provide stability for the vehicle cars and an additional rail to power the cars as is typical for the 3rd rail for electric trains. The key track requirements are that the track be circular (track radius is constant), level (perpendicular to the gravity vector), and have a constant superelevation angle with respect to the gravity vector. The

track foundation is implemented with a reinforced steel and concrete ring to minimize track deformation over time.

An optional augmentation to the track design concept presented is for the tracks to support maglev cars to minimize their energy use, noise, vibration, and wear. At low speeds and in emergency cases the vehicle wheels would contact the tracks, but during nominal operations the vehicles do not contact the tracks other than for power. Once the HGV reaches a significant operating speed, the passengers will not easily detect that the cars are moving. However, they will be able to detect their bodyweights and cabin content weights have increased.

Figure 14 illustrates the ESHGV completely filled with HGVCs and the Transfer Vehicle (not to scale). However, the ESGV can easily be incrementally completed and operated in a minimal configuration of a single HGVC without the Transfer Vehicle.

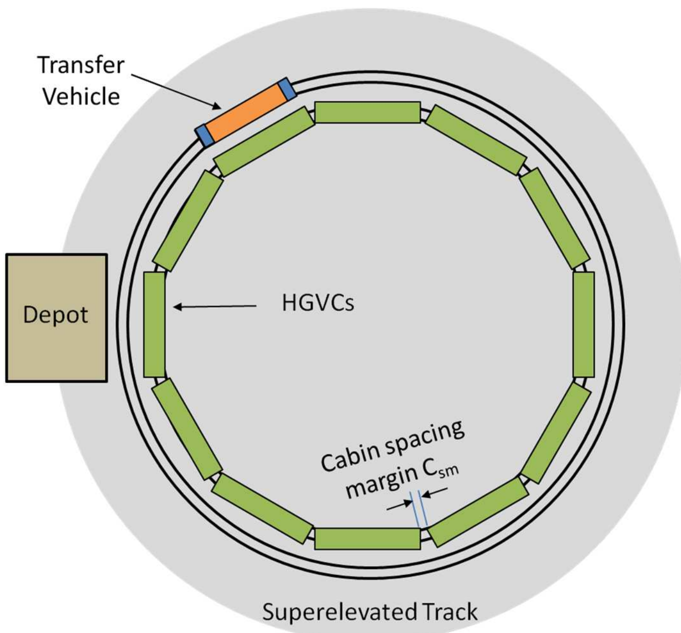


Figure 14: ESHGV System depicted in a HGV complete ring configuration (figure not to scale)

The HGVCs must be spaced with sufficient margin between cabins to prevent contact between cabins when tilted. This spacing is discussed further in appendix C.

2.4 Transfer Vehicle Subsystem Overview

The top view of a Transfer Vehicle aligned with a multi-car HGV is shown in Figure 14.
The purpose of the Transfer Vehicle is to transfer people and cargo between the Depot and the HGV while the HGV is running so that the HGV can indefinitely maintain a constant velocity and minimize disruptive hypergravity-level changes. In addition, using a Transfer Vehicle reduces the energy required to operate the ESHGF since the entire HGV, which can be several times the mass of the Transfer Vehicle, does not have to stop and restart every time someone or something needs to go on or come off it. The Transfer Vehicle subsystem is similar in design to a single-car HGV, as shown in Figure 7 and Figure 8, but may be shorter depending on the transfer

capacity required. Also, the Transfer Vehicle may be augmented with a cabin elevator as shown in Figure 16.

The Transfer Vehicle cabin is equipped with a Retractable Vestibule for ingress and egress with the HGV and two chassis Retractable Arm Locks for the Transfer Vehicle and HGV to maintain a constant relative position while docked to each other. At least one HGVC is equipped with two Retractable Arm Locks and a docking port for the Transfer Vehicle Retractable Vestibule as depicted in Figure 15 and Figure 16.

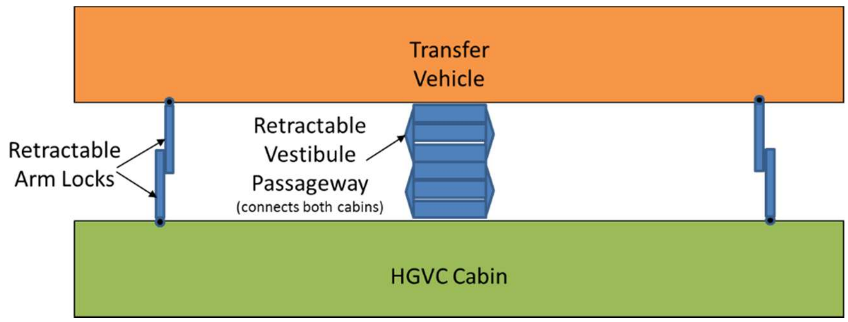


Figure 15: Transfer Vehicle temporarily connected to HGVC Top View

In this design concept, the Transfer Vehicle and its track either can be designed for docking with the HGV at its entire range of velocities and corresponding cabin pivot angles or for only docking at a specific HGV velocity and cabin pivot angle. In order for the Transfer Vehicle to dock with the HGV at a range of velocities the Transfer Vehicle is required to elevate as well as tilt its cabin for docking. This is accomplished with a cabin elevator that raises and lowers the Transfer Vehicle cabin and its tilt mechanism as shown in Figure 16 and Figure 17.

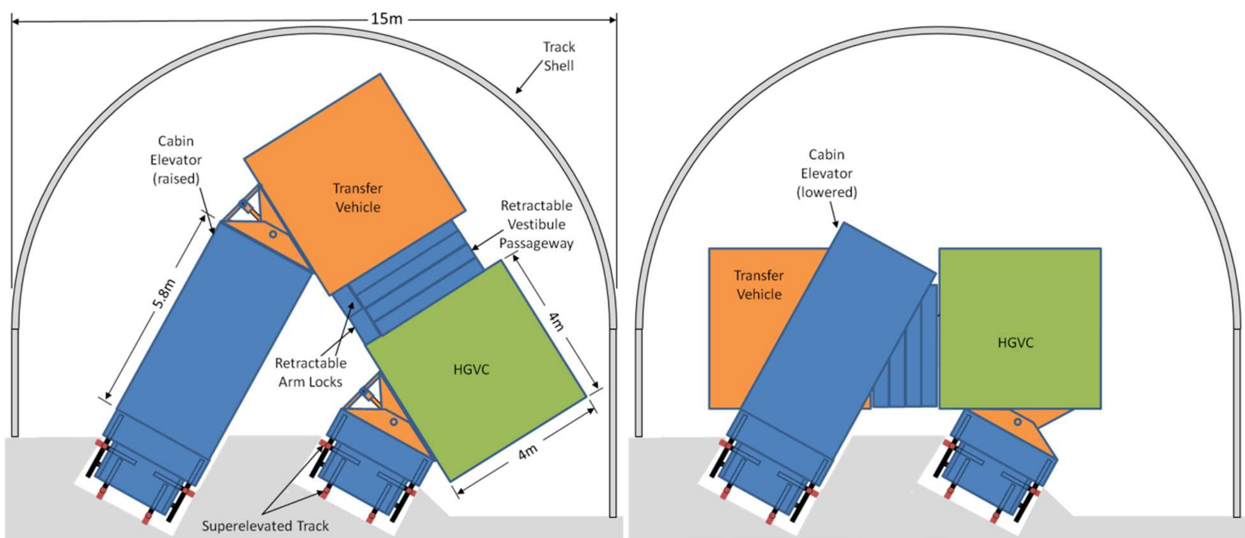


Figure 16: Transfer Vehicle Docking with HGVCs Rear Views in Max g Orientation (left) and Stopped Orientation (right)

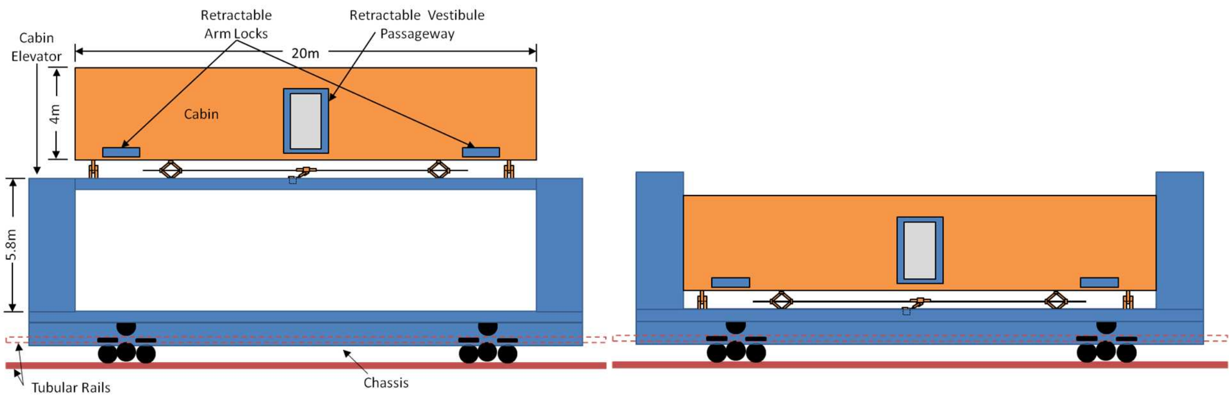


Figure 17: Transfer Vehicle Side Views
Cabin Elevator Raised (left) and Lowered (right)

However, the Transfer Vehicle is not required to elevate its cabin if it is designed only to dock when the HGV is at a specific operating speed and cabin angle as shown in Figure 18.

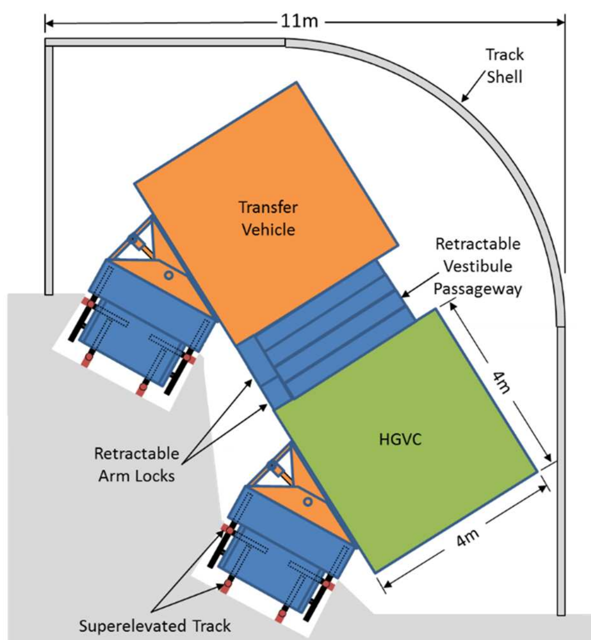


Figure 18: Transfer Vehicle temporarily connected to HGVC Rear View

A design alternative to the Transfer Vehicle Retractable Vestibule is for the entire Transfer Vehicle Cabin to translate horizontally and vertically to directly dock with an HGV Cabin. An alternative to the entire Transfer Vehicle subsystem is the Hub & Spoke subsystem discussed in section 2.8.3.

2.5 Depot / Control Center Subsystem Overview

The Depot / Control Center (DCC) subsystem (see Figure 14) controls the HGV and Transfer Vehicle and is similar in design and function to train stations and airport terminals. The DCC facilitates the ingress and egress of people, animals, plants, equipment, supplies, utilities,

workproducts, waste, and data between the ESHGF and outside the system. The DCC also acts as a service station for the HGV and Transfer Vehicle.

2.6 HGV HyperGravity

2.6.1 HGV HyperGravity Level

The hypergravity level of the HGV is the vector sum of the ambient gravity vector at the HGV location and the perpendicular centripetal-acceleration vector created by the HGV travelling in a circle. The hypergravity level at a point in an HGVC cabin is a function of the track radius and HGVC velocity at that point and is defined by Equation 1. The HGVC Cabin coordinate frame is defined with its origin at the center of the bottom of the cabin; the +x-axis runs lengthwise toward the cabin front; the +y-axis runs widthwise directly opposed to the track center; and the +z-axis runs up toward the cabin ceiling.

The HGVC cabin coordinate frame changes with respect to its HGVC coordinate frame by the cabin pivot angle P, which changes the radii and velocities of the points in the cabin respectively according to Equation 1. The cabin point velocities vary within the cabin per Equation 2, but the overall HGVC velocity, v_W, is controlled by the HGVC wheel truck.

$$H_{pos}(x,y,z,P,v_W,g_a) = \frac{\sqrt{g_a^2 + \left(\frac{v_{pos}(x,y,z,P,v_W)^2}{r_{pos}(x,y,z,P)}\right)^2}}{9.807}$$

Equation 1: Hypergravity Level

$$v_{pos}(x,y,z,P,v_W) = \frac{v_w \cdot r_{pos}(x,y,z,P)}{r_T}$$

Equation 2 : HGVC Cabin Point Velocity

where:

$H_{pos}(x,y,z,P,v_W)$ = HGV hypergravity level in Earth gravity g's at the HGVC cabin coordinates (x, y, z) at cabin pivot angle P at HGVC wheel truck velocity v_W (Earth g)

r_T = Track Circle Radius measured from center of upper track gauge (m)

$r_{pos}(x,y,z,P)$ = Cabin point radius at cabin coordinates (x, y, z) at cabin pivot angle P from HGV track circle center (m)

$v_{pos}(x,y,z,P,v_W)$ = HGVC velocity at cabin coordinates (x, y, z) at P and at v_W (*m/s*)

v_W = HGVC wheel truck velocity = HGV velocity (m/s)

P = Cabin Pivot Axle Angle (degrees)

g_a = Ambient gravity at the ESHGF location. For example:

- Earth $g_a = 9.807 m/s^2$
- Mars $g_a = 3.711 m/s^2$
- Moon $g_a = 1.622 m/s^2$
- On orbit $g_a = 0 m/s^2$

Note that changing the Cabin Pivot Axle Angle P changes the radii and velocities of the points in the HGVC Cabin even though the HGVC RPM on the track remains constant. Hence, track radius r_T is a rough approximation of the actual radius of an HGVC cabin point, $r_{pos}(x, y, z, P)$; and consequently the HGVC wheel truck velocity v_W is a rough approximation of the HGVC cabin point velocity, $v_{pos}(x, y, z, P, v_W)$. These approximations do not hold for cases in which the track radius r_T is small relative to the cabin width y and height z, such as for an extreme case in which tilting the cabin places the track circle center underneath cabin points (the velocity is 0 for cabin points directly over the track circle center regardless of the HGVC RPM). A precise definition of $r_{pos}(x, y, z, P)$ is in Appendix B.

Equation 1 is derived from the equation defining centripetal acceleration ($a=v^2/r$), and the equation for adding two perpendicular vectors (Pythagorean Theorem). Note that the hypergravity (minus the ambient gravity) is inversely proportional to the track diameter, but is directly proportional to the square of the HGV velocity. For example, halving the track diameter doubles the gravity increase due to centripetal acceleration; but doubling the HGV velocity quadruples the gravity due to centripetal acceleration. Table 1 provides more detailed examples.

Location	HGV Ambient (Location) Gravity (m/s^2)	Track Dia (m)	HGV Velocity (m/s)	HGV MPH	HGV RPM	Cabin Angle (deg)	Track Super-elevation (deg)	Centripetal Acceleration (Horizontal) g's	HGV Hyper-gravity g's (H)
Earth	9.807	100	0	0	0.0	-30	30	0.00	1.00
Earth	9.807	100	10	22	1.9	-18	30	0.20	1.02
Earth	9.807	100	20	45	3.8	9	30	0.82	1.29
Earth	9.807	100	35	78	6.7	38	30	2.50	2.69
Earth	9.807	250	25	56	1.9	-3	30	0.51	1.12
Earth	9.807	250	35	78	2.7	15	30	1.00	1.41
Earth	9.807	250	50	112	3.8	34	30	2.04	2.27
Earth	9.807	300	25	56	1.6	-7	30	0.42	1.09
Earth	9.807	300	40	89	2.5	17	30	1.09	1.48
Earth	9.807	300	50	112	3.2	30	30	1.70	1.97
Earth	9.807	500	25	56	1.0	-16	30	0.25	1.03
Earth	9.807	500	50	112	1.9	16	30	1.02	1.43
Earth	9.807	500	75	168	2.9	36	30	2.29	2.50
Mars	3.711	250	34	76	2.6	33	35	0.94	1.02
Mars	3.711	300	37	83	2.4	33	35	0.93	1.00
Mars	3.711	500	48	107	1.8	33	35	0.94	1.01
Moon	1.622	250	35	78	2.7	41	40	1.00	1.01
Moon	1.622	300	38	85	2.4	40	40	0.98	1.00
Moon	1.622	500	50	112	1.9	41	40	1.02	1.03
On-orbit	0	250	35	78	2.7	0	0	1.00	1.00
On-orbit	0	300	38	85	2.4	0	0	0.98	0.98
On-orbit	0	500	50	112	1.9	0	0	1.02	1.02

Table 1: Hypergravity Level Examples

Note that the g's calculated in Table 1 do not take into account small variances due to HGV dimensions, such as the cabin floor height, width, and length, to be discussed in section 2.6.3.

Table 1 captures a number of the trades in order to obtain the desired hypergravity level. For a given hypergravity level, the required HGV velocity can be reduced by decreasing the track diameter, but this also increases the HGV RPM. Large track diameters increase costs and high HGV velocities increase risks, but high RPMs increase the likelihood and intensity of motion sickness and possible long-term side effects. The long-term effects of rotation on humans is not well understood (excluding one revolution per day), but rates above 2-3 RPMs are known to cause motion sickness in a high percentage of the population when not trained or treated accordingly. The capability to study these long-term effects is one of the benefits of the ESHGF.

Additional examples are given at various HGV velocities with four different track diameters (100m, 250m, 300m, and 500m), at four different locations (Earth, Mars, Moon, and on-orbit) for considering the ESHGF as an analogue for off-Earth artificial-gravity facilities. The on-orbit example rows are provided since such an ESHGF would be similar to an orbiting space station in a wheel configuration with spokes and connected rim modules instead of tracks and HGV cars. The on-orbit examples are also similar to ESHGFs on an asteroid or Mars moon. Note that once the ambient gravity of the ESHGF is reduced to the gravity level of the Moon (1.622 m/s^2), the ambient gravity has little effect on the hypergravity level (H) when the centripetal acceleration is several times higher than the ambient gravity (as shown in Table 1).

The optimal track diameter of 300m for this design concept is shown by the highlighted rows in Table 1. A design with a hypergravity level of up to 2g's is required to provide the capability to generate a wide range of hypergravity levels humans can live at for long periods. Smaller track diameters require an RPM levels that are too high for a 2g hypergravity level. For larger diameters for a 2g hypergravity level, the HGV velocities are too high as well as being more costly. An HGV configured as the third highlighted row is shown in perspective in Figure 9. For this example, the track is 300m diameter with a 30° superelevation and a Cabin Pivot Angle of an additional 30°. This HGV has a hypergravity of 1.97g when running 50m/s (112mph), which is 3.2 RPMs. The 300m diameter is also a reasonable size for an orbiting space settlement, which would generate 1g at 2.4RPMs.

An ESHGV can be designed with multiple concentric tracks of different diameters to support simultaneously generating multiple levels of hypergravity. Multi-track ESHGF designs are discussed in 2.8.

2.6.2 HGV Hypergravity Control

The hypergravity is controlled by controlling the HGV velocity per Equation 1. Consequently, the hypergravity can be kept constant by maintaining a constant HGV velocity

In addition to controlling the hypergravity level of the HGV, the HGV controls the cabin tilt angle per Equation 3 so that regardless of the HGV velocity, the down direction (hypergravity vector) is always perpendicular to the center of the cabin floor as shown in Figure 19. The Cabin Angle specified in Table 1 is measured with the vertex at the center of the HGV pivot such that at a Cabin Angle of 0 degrees, the cabin floor is parallel with the chassis bed and track

superelevation. The sum of the Cabin Angle and the Track angle is the angle of the cabin floor to the track circle plane, which is perpendicular to the ambient gravity vector, i.e., level.

For example, consider the first example in Table 1. The HGV is stopped on a track with a 30° superelevation. The Cabin Angle is -30° in order to maintain the down direction perpendicular to the cabin floor. This case is illustrated in Figure 19 left.

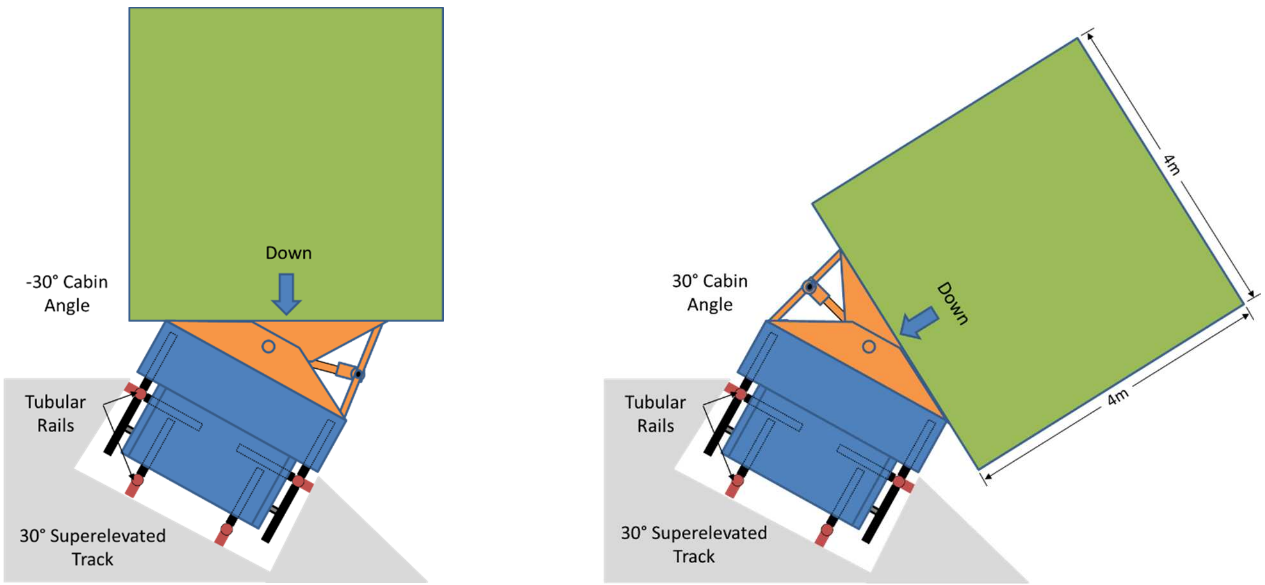


Figure 19: HGV Car in Stopped Orientation (left) and Max g Orientation (right)

As the HGV velocity increases, the Cabin Angle increase until it reaches its maximum value of 30° as depicted in Figure 19 right.

With a sufficiently slow HGV acceleration rate and Cabin Angle change rate, neither change will be noticed by the occupants. For example, a glass of water resting on a table would appear to remain unchanged as the HGV accelerates and then maintains its operational velocity. The only difference with regard to the glass of water is that it would become heavier.

In order to maintain a constant down direction at any velocity, the tilt command input is maintained at the calculated cabin tilt angle, which is a function of the HGV velocity and is defined by Equation 3.

$$P = \tan^{-1}\left(\frac{v_W^2}{r_T \cdot g_a}\right) \cdot \frac{180}{\pi} - T_B$$

Equation 3: HGV Cabin Tilt Angle

where:
P = HGV Cabin Pivot Axle Angle (degrees)
T_B = Track Superelevation (Bank) Angle (degrees)
g_a = Ambient gravity at the ESHGF location.
v_W = HGVC wheel truck velocity = HGV velocity (m/s)

r_T = Track Circle Radius (m)
r_{bias} = Track Circle Radius bias (m)

The Track Circle Radius bias is a HGVC tunable parameter, nominally between 0 and 2, that is used to fine-tune the cabin pivot angle since the hypergravity level does vary slightly throughout the cabin as described in the next section.

2.6.3 HGVC Cabin Gravity Map

Ideally, the hypergravity level would be equal and constant for all points in a HGVC cabin for the gravity to behave more like the way people are accustomed to on Earth and for consistency in experiments. However, there will be minor gravity variations at different points in the cabin that are different distances from the center of the HGV track circle and consequently have different centripetal accelerations and corresponding hypergravity levels. The advantage of using a large radius track is that these variances are minimal. In an extreme case where the track circle is so small that the track radius is zero for points in a HGVC cabin, the centripetal acceleration for an object centered at such a point would also be zero. An example of an HGVC Cabin hypergravity floor map illustrating these microgravity variation is shown in Figure 20.

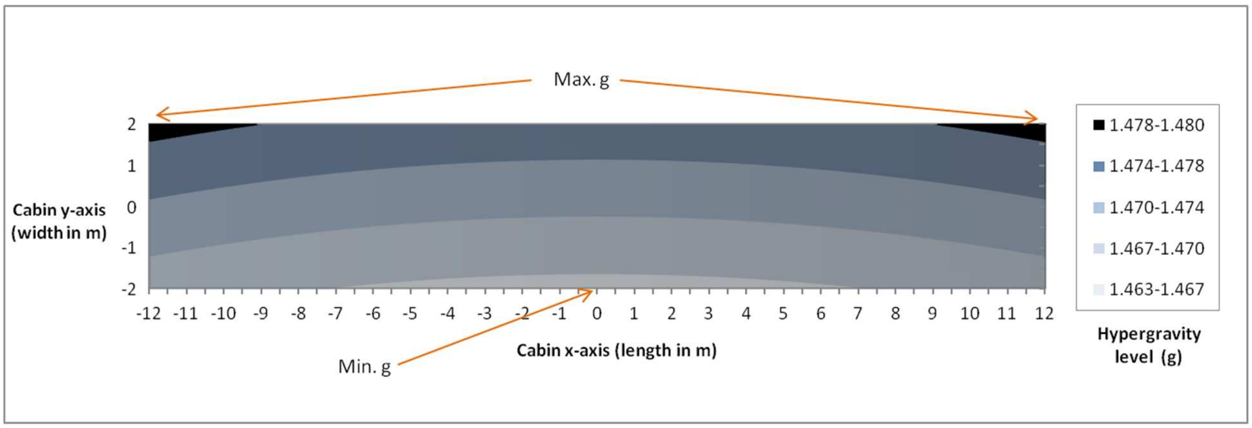


Figure 20: HGVC 24 x 4m Floor Hypergravity Map Example

Pertinent parameters for this example are the HGVC cabin coordinates (x, y), the Cabin Pivot Angle = 30°, the track radius = 150m, the HGV velocity=40m/s, track superelevation angle = 30°, Cabin Pivot Center height=1m, Cabin floor height from pivot axle center=0.5m, Cabin length=24m, Cabin width=4m, front & rear wheel truck offset=3m, and ambient gravity=9.807m/s^2 (Earth); the relevance of these parameter are discussed below.

This hypergravity map changes with different HGV configurations and velocities, but in most cases the basic characteristics are similar. The hypergravity varies with the (x, y, z) position of an object in the HGV cabin. The lowest-hypergravity point on the cabin floor is at the middle of the cabin where the floor meets the inner wall, i.e., position (0, -2). The hypergravity at this position for this example is 1.466g's, so a 1kg mass at this position would weigh 1.466kg. However, the hypergravity at both outer corners, positions (-12, 2) & (12, 2), is 1.479g's, so a 1kg mass at both of those locations would weigh 1.479kg, 13 grams more, an increase of ~1%. In most cases, a variation of 1% would not be noticeable, but it is a design consideration. This variation increases considerably on smaller diameter tracks. Although the floor is flat, water

would tend to flow and balls would tend to roll away from the inside center to the outside corners of the cabins, with an asymmetric bias toward the rear outside corner since any object moving away from the track circle center will gain momentum in the process. This effect is less within each cabin room since they are smaller.

The length, width, and height of the HGVC Cabin all effect these variations. A person moving directly across a cabin from its outside wall to its inside wall also moves further toward the center of the track circle and reduces the person's rotation radius. By increasing the sum of the track superelevation angle and cabin pitch angle to 90° such that the cabin floor is perpendicular to the track plane, a change in width position will no longer cause a change in hypergravity. However, such a configuration is only appropriate in a microgravity environment such as an orbiting space settlement. Reducing the width of the HGVC Cabin will also reduce this variance, but this also can be accomplished by creating narrower rooms within the HGVCs as needed.

Since the cabins are straight instead of arced with the same radius as the track, moving toward the length center of a cabin also moves further toward the center of the track and reduces the spin radius (each cabin is a chord of the track circle – see Figure 13 & Figure 31). This variance can be mitigated by arcing the floor and shortening the HGVC cabin length or cabin room lengths.

The hypergravity level changes as an object is raised in the Cabin, i.e., an object on a table in the cabin will weigh less than the same object on the floor directly below it (with respect to the Cabin coordinate frame). Since the Cabin is tilted toward the track circle center, increasing the height of an object decreases its track circle radius and its corresponding centripetal acceleration.

2.7 ESHGF Modularity

A key feature of the ESHGF is its modularity. Each module, comparable to intermodal shipping containers, can be transported by rail, truck, ship, and aircraft as shipping containers currently are transported. The size of these modules are also feasible for heavy lift launch vehicles. If necessary, the ESHGF Cars and/or Modular Cabins can be separated, transported, and reattached at their destination. When being transported, in some cases the self-leveling tilt mechanism can be activated to mitigate lateral acceleration during transport as needed to protect the contents and to enable the continued operation of the Cabins during transport. Also, ESHGF Cabins and Cars can be added as needed to increase system capacity, as well as be removed for maintenance, to be upgraded, or replaced with modules tailored for different purposes.

2.8 ESHGF System Capacity and Extensibility

Significant artificial-gravity research can be accomplished with a single HGVC, but with the goal to ultimately create a scalable space habitat to support a permanent space community in excess of 1000 people, the ESHGF can be incrementally expanded to support such population-sizes as well as habitats for a wide variety of plants and animals.

The modular characteristic of the ESHGF design enables the system capacity to be incrementally increased as needed. The design presented focuses on a 300m diameter track, but as discussed previously, other track sizes may be implemented. Capacity can be increased in a number of ways. In this section, the following methods to increase capacity are presented: increasing the

number of Cabins per HGVC, increasing the number of HGVCs per track, and increasing the number of concentric tracks.

2.8.1 HGV Population Density

The population density of the HGV can vary significantly based on the operations concept. An HGV could be operated unmanned as the lower bound of population density. An upper bound for consideration is provided by the U.S. Code of Federal Regulations Title 46 - Shipping which permits up to one person per each 0.9m^2 of deck area (U.S. Federal Government, 2011).

However, a cruise ship may provide a more reasonable estimate for long-term population density. A population density analysis of a small sample of Royal Caribbean cruise ships is shown in Table 2. More on these cruise ships at: (Royal Carribean International, 2015).

Ship Name	Max. Passengers & Crew	Total Deck Area (m^2)	Deck Area per Person (m^2)	Reference
Adventure of the Seas	5,020	137,000	27	(Kable Intelligence Limited, 2015)
Mariner of the Seas	5,020	145,000	29	(Cybercruises.com, 2003)
Navigator of the Seas	5,364	137,000	26	(Trauthwein, 2003)
Freedom of the Seas	5,740	165,000	29	(MarineLink.com, 2005)

Table 2: Cruise Ship Population Density Examples

Based on an average cruise ship population density of 28m^2 per person, a corresponding HGV population at the same density is 3.43 people per single cabin car. In the following section, multi-cabin cars are presented that increase the population up to 48 people per car, at the same density depending on the number of cabins added.

2.8.2 Multi-Cabin HGVCs

Multiple cabins can be attached to a single HGVC to increase the HGV capacity and to generally reduce the path distance between two points in different cabins compared to cabins configured linearly on single-cabin HGVCs.

The simplest multi-cabin HGVC has a second cabin on top of the first as illustrated in Figure 21. This configuration doubles the HGVC deck area to 192m^2 (2,067 sq. ft.) without increasing the chassis size.

This figure also illustrates the ESHGF can be implemented in circular tunnel, similar to a subway, instead of using a track shell. This is a more realistic analogue for an artificial-gravity facility on Mars, a moon, or an asteroid, which would benefit from the shielding and thermal insulation being underground provides. If Tunnel Boring Machines (Maidl, Schmid, Ritz, & Herrenknecht, 2008) (Zhao, 2012) are used for mining in these locations, the tunnels they leave behind can be used for artificial-gravity settlements.

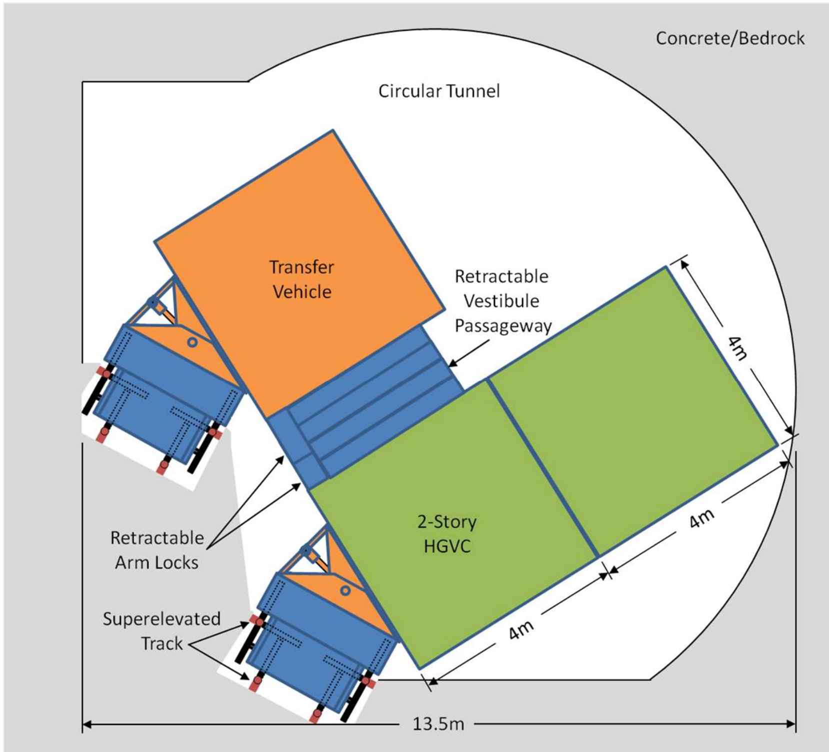


Figure 21: 2-Story HGVC docking with a Transfer Vehicle on a Tunnel Track

Once HGVCs with one or two cabins have been validated, HGVCs with many more cabins can be deployed by increasing the HGVC chassis width and track gauge as needed to accommodate the loads of the cabins and their contents. Additional rails can be added if needed as well.

Multiple views of a 26 cabin, chassis HGVC configuration are shown in and Figure 22 and Figure 23. In Figure 22, side-by-side perspective views of this 26-Cabin HGVC on a 300m diameter 30° superelevated track are shown. The left view illustrates the HGVC stopped for loading with a Cabin Pivot Angle of -30°. The right view illustrates the same HGVC with a Cabin Pivot Angle of 30° required for 2g of hypergravity.

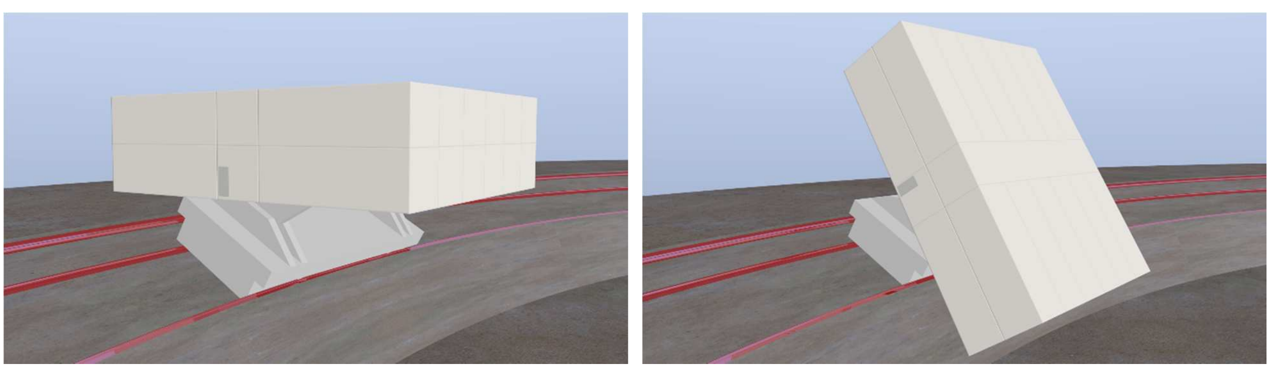


Figure 22: 26-Cabin HGVC on Track Perspective View
Stopped (left) and at 2g orientation (right)

This 26-Cabin HGVC is sized to be suitable as an analogue of one of the 36 10° arc rim segments required for a fully-implemented 300m dia. wheel-shaped space settlement, such as those depicted in Figure 1 and Figure 3. This is also a 2-story configuration in which the two center cabins, mounted directly above the HGVC chassis, are 24 x 4 x 4m in size. The remaining 24 cabins are half the length (12 x 4 x 4m). Openings and stairways between these cabins can be added as needed. The floor space for this configuration for each HGVC is $1344m^2$ (14,467 sq. ft.).

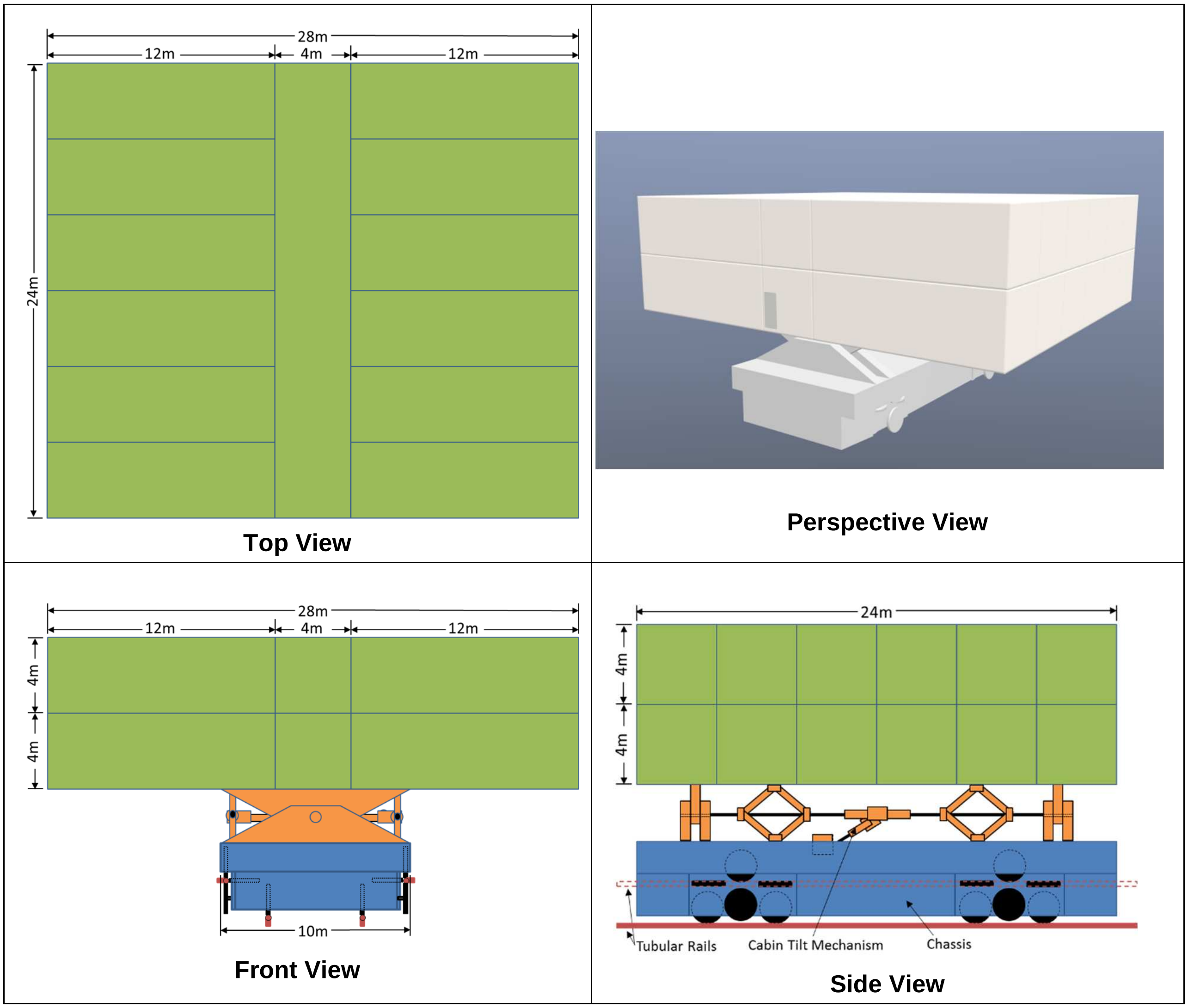


Figure 23: 26-Cabin HGVC Views

The tracks and the HGV chasses can be designed to support the loads as needed. In most cases, the 4-rail track described in this design concept should be sufficient. The HGVC design specifies 10 wheels per wheel truck and 2 wheel trucks per chassis (Figure 13). To provide context, cargo trains are currently operational that support 40,000kg per 2-wheel axle (Kirk, 2008).

2.8.3 ESHGF Hub-and-Spoke Subsystem Architecture

An alternative to the Transfer Vehicle is a rotating Hub-and-Spoke subsystem in which the Hub is located at the center of the concentric tracks and rotates at the same velocity as the HGV. This architecture is a closer analogue to that of an orbiting space settlement. Figure 24 depicts a single HGV consisting of 36 HGVCs, each with 26 cabins as defined in section 2.8.2. To accommodate these HGVCs, a 315m diameter track is required (see Appendix C). With each HGVC vertically oriented such that the top faces the track center, as would be the case for an on-orbit implementation, the spacing between the HGVCs would be reduced, reducing the overall diameter to 300m.

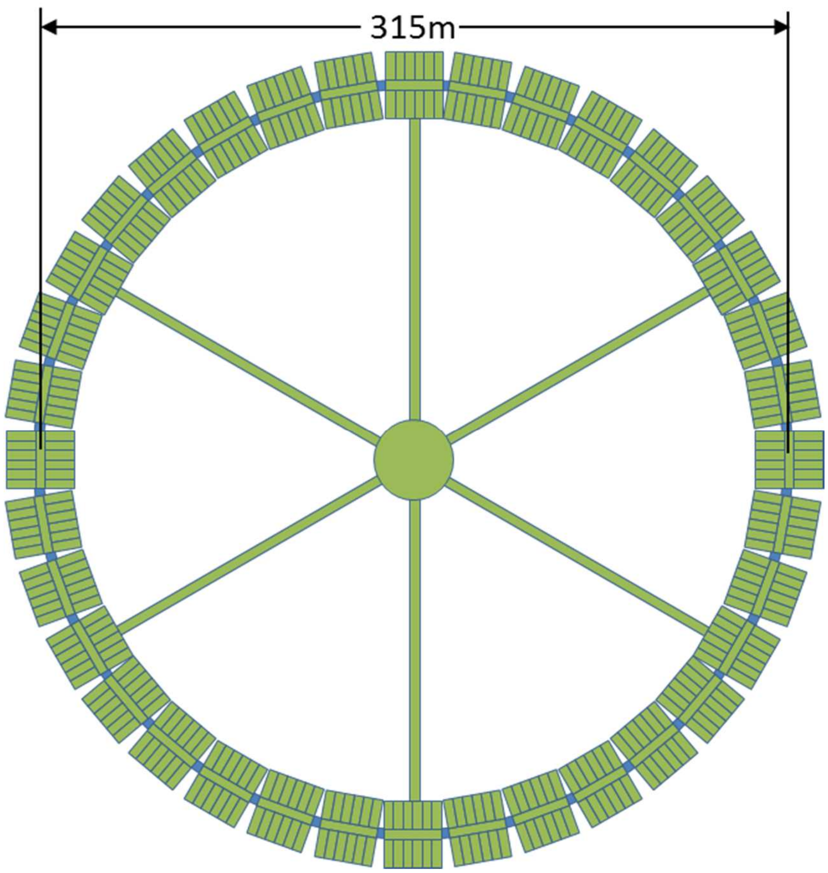


Figure 24: Single Ring 26-Cabin 36-HGVC ESHGF Top View

The total cabin deck area of this configuration is 48,384m^2 (520,801ft^2), excluding the Spoke area and not accounting for deck area lost to accommodate Spoke connections. This deck area supports a population of 1,728 at cruise ship density. Note that this configuration can be implemented incrementally, one cabin or one HGVC at a time.

As depicted in Figure 24, each Spoke projects from the Hub and attaches to HGVCs. Figure 24 shows the Spokes connecting to the end of the cabins to simplify the illustration, but designs that entail the removal of some HGVC cabins and connecting each Spoke directly to an HGVC chassis at its midpoint or between two adjacent HGVCs at their vestibule passageway are viable

alternatives. Several methods to attach the Spokes to the HGVCs are feasible and require further analysis. The Spoke/HGVC connection design is beyond the scope of this document.

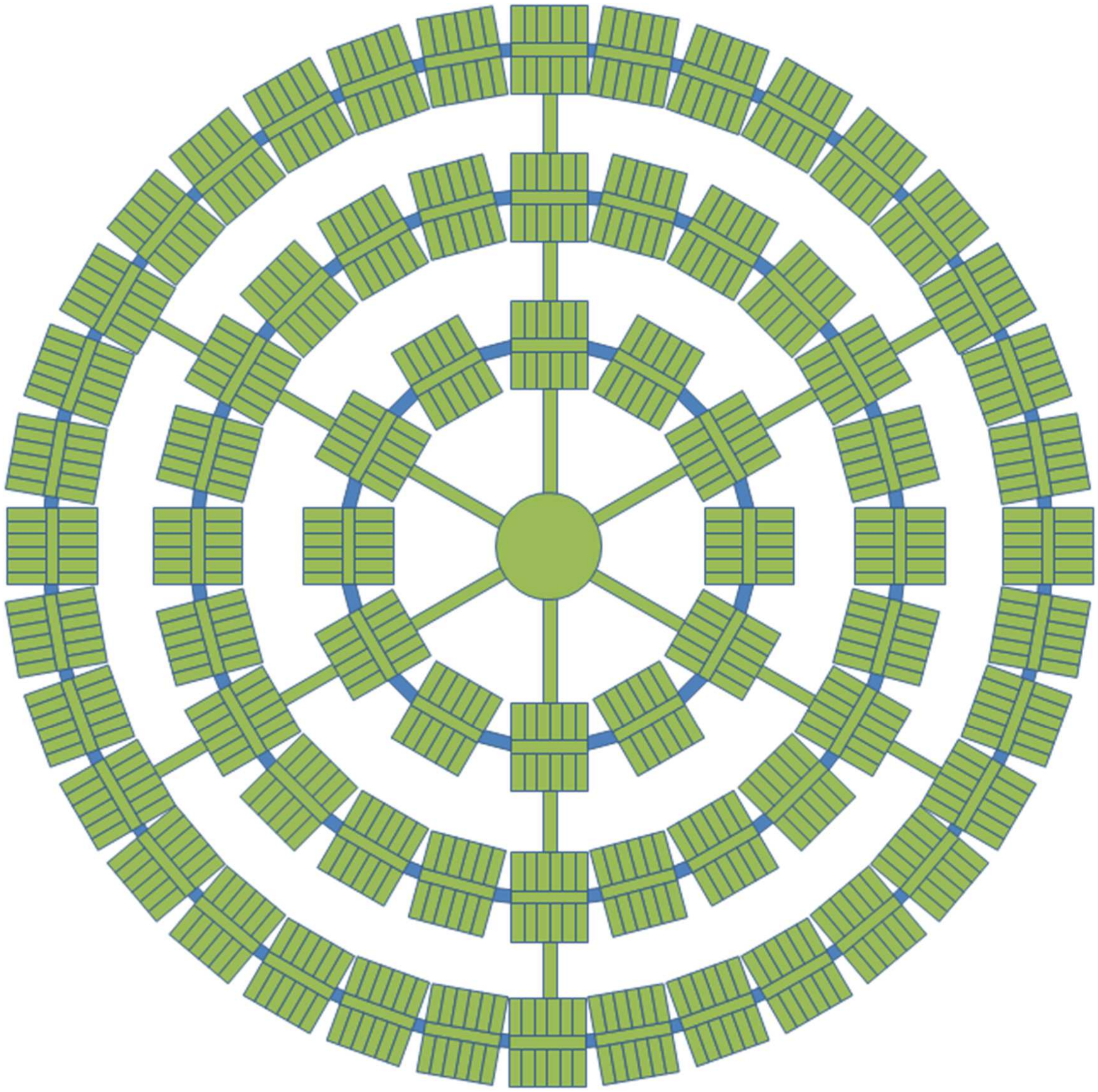
Within each Spoke are passageways to transfer people, animals, plants, and supplies between the Hub and HGVC as does the Transfer Vehicle. Each 4m-wide Spoke provides ample room for a pair of tilting elevators (or escalators), a cargo cart passageway, and a service passageway as well as conduits for wires, fibers, and pipes to transfer power, data, and fluids respectively. The Spokes may be supported by trollies running on concentric tracks underneath them and by suspension cables from the Hub peak as needed.

The Hub-and-Spoke subsystem can also support multiple HGVs in concentric rings as shown in Figure 25. An ESHGF with multiple rings has the advantages of increasing capacity as well as providing an increased variance in hypergravity and rotation radii to better characterize their different effects. Also, an orbiting space settlement may require multiple gravity levels to support crew and visitors preparing for or recovering from low-gravity environment missions.

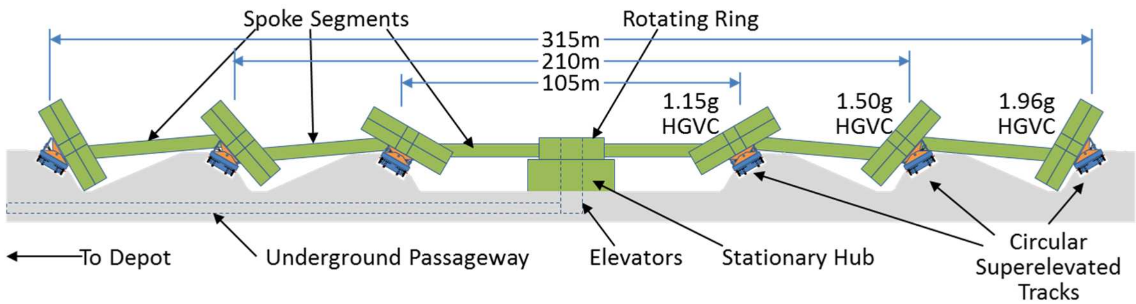
Figure 25 depicts three concentric HGVs consisting of a total of 72 HGVCs, each with 26 cabins. The outer HGV is identical to the 36 car HGV shown in Figure 24. By adding two concentric HGVs, one with 24 HGVCs and the other with 12 HGVCs, the capacity is doubled. The total cabin deck area of this configuration is 96,768m^2 (1,041,601ft^2). This supports a population of 3,456 at cruise ship density.

Similar to a rotating restaurant on a tower, the central Hub either can be designed to entirely rotate on a small concentric track of trolleys or be designed as a cylinder rotating around a stationary vertical axle. At rotation rates of 2-3RPM transitioning between the rotating and stationary portions of the Hub would be similar to getting on and off an escalator. The Hub can be connected to the MCC by a tunnel under the ESHGF and/or a bridge.

The Hub-and-Spoke subsystem has the advantage of allowing a continuous flow of people, animals, plants and supplies on and off the ESHGF as needed. Also, it provides a closer analogue to an off-Earth artificial-gravity facility in which the Hub would be at the ambient gravity of the ESHGF location, e.g., microgravity on orbit, and Mars gravity on Mars.



Top View with all HGVCs at a horizontal orientation (1g)



Side View of the 6 HGVCs on opposing Spokes at 3.1 RPM operation orientations

Figure 25: Triple Ring 26-Cabin 72-HGVC ESHGF

2.8.4 ESHGF Hub-and-Spoke Shell

Unlike the torus shell or tunnel that can be used to protect an HGV that uses a Transfer Vehicle, as shown in Figure 16, a different shell design is required for the optional but recommended shell for a Hub-and-Spoke ESHGF. This shell design uses flexible stadium roofing material. However, unlike stadiums which do not use a center support, The ESHGF uses a stationary 45m tower at the center ESHGF hub, essentially acting as the axle that the hub ring rotates around, to support the roof. Suspension cables attach from the center tower peak to a circular outer wall that surrounds the ESHGF on the other end. The combination of the center tower, the suspension cables, and the 350m dia. x 10m high outer wall support the that ESHGF roofing material as depicted in Figure 26. This exterior is suitable for housing the Triple Ring 26-Cabin 72-HGVC ESHGV shown in Figure 25.

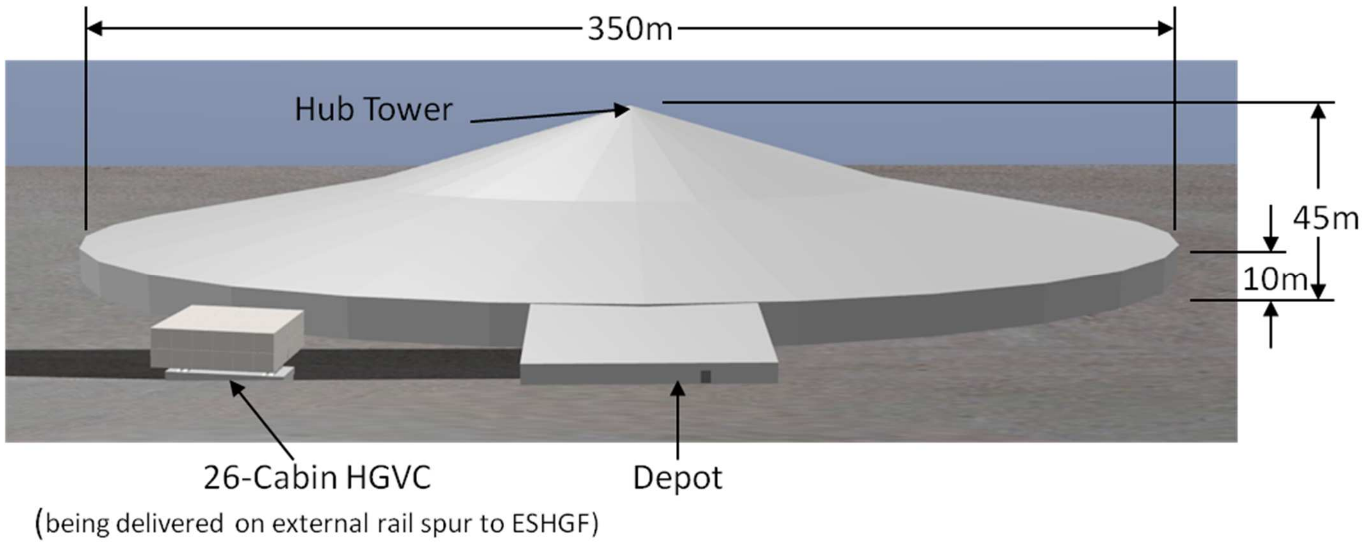


Figure 26: ESHGF Exterior for a Hub-and-Spoke HGV with a 315m dia. Track

The interior of the ESHGV can also be slightly pressurized to provide additional support.

2.8.5 ESHGF Hub-and-Spoke Subsystem Incremental Implementation

The ESHGF Hub-and-Spoke Subsystem can be incrementally implemented in a variety of configurations. Incremental implementation of an ESHGF on Earth can also be used to reflect how an on-orbit artificial-gravity facility may be incrementally implemented to help mitigate its development risks. The following figures illustrate how different configurations of 26-Cabin HGVCs can be extended. Similarly, the number of cabins for each HGVs can be incrementally increased starting with single-cabin HGVCs.

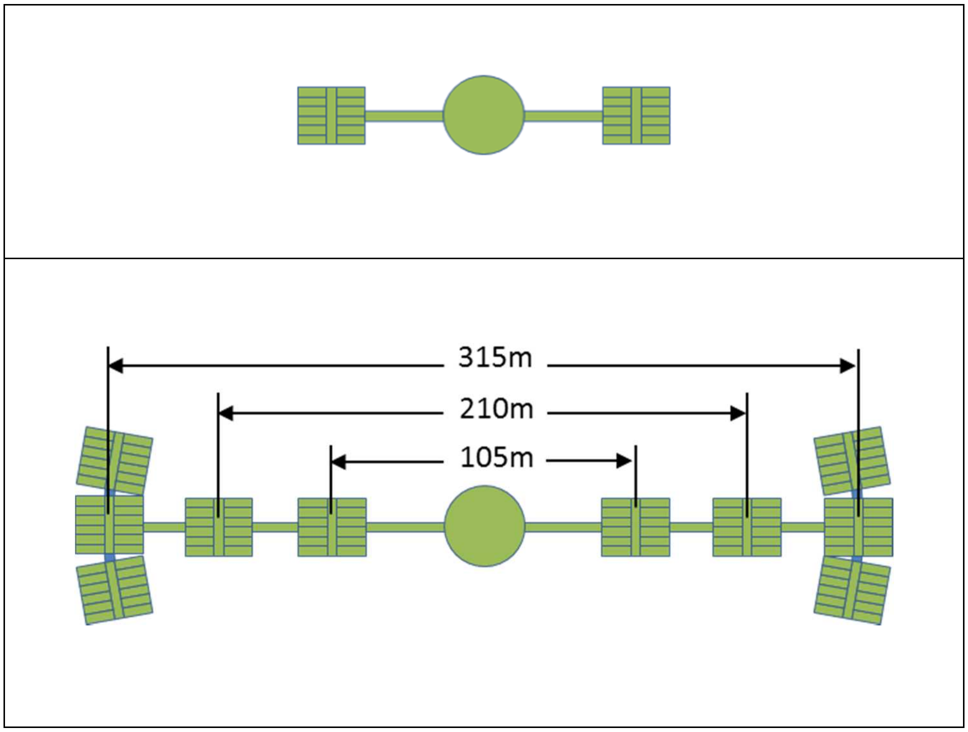


Figure 27: ESHGF Incremental Implementation with 26-Cabin HGVCs in 'I' Configuration Top View Implementations: 2-HGVC (top), 10-HGVC (bottom)

The 'I" configuration shown in Figure 27, also referred to as the "dumbbell" configuration, is a 2-Spoke configuration that is a relatively low-cost and is a reasonable configuration when low-capacity is suitable. This configuration has a disadvantage when implemented on-orbit that the lengthwise axis is not stabilized when it rotates about the Hub (Sanyal, Shen, McClamroch, & Bloch, 2005). However, this can be passively mitigated by adding HGVCs at the outer end of each Spoke as shown in the bottom of Figure 27.

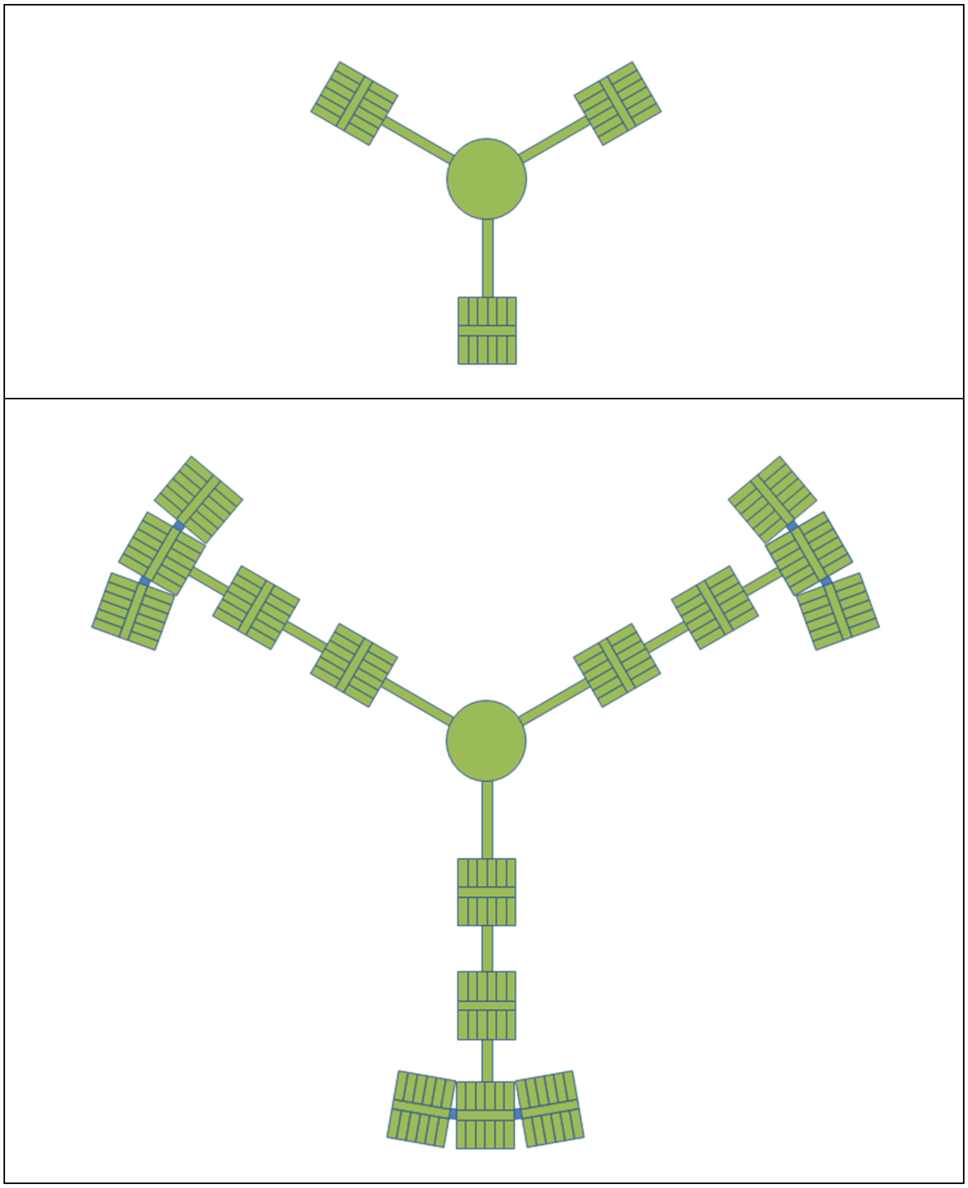


Figure 28: ESHGF Incremental Implementation with 26-Cabin HGVCs in ‘Y’ Configuration Top View Implementations: 3-HGVC (top), 15-HGVC (bottom)

The ‘Y’ configuration shown in Figure 28 is a 3-Spoke configuration that has the benefit of being spin-stabilized in all three axes when rotated. Also, on-orbit two ‘Y’ configurations can be combined into a single 6-Spoke configuration as shown in Figure 25 or attached at their hubs and counter-rotated to keep the net angular momentum of the combined facility near zero regardless of the rotation rate. This has the benefit of not requiring propellant to despin if necessary.

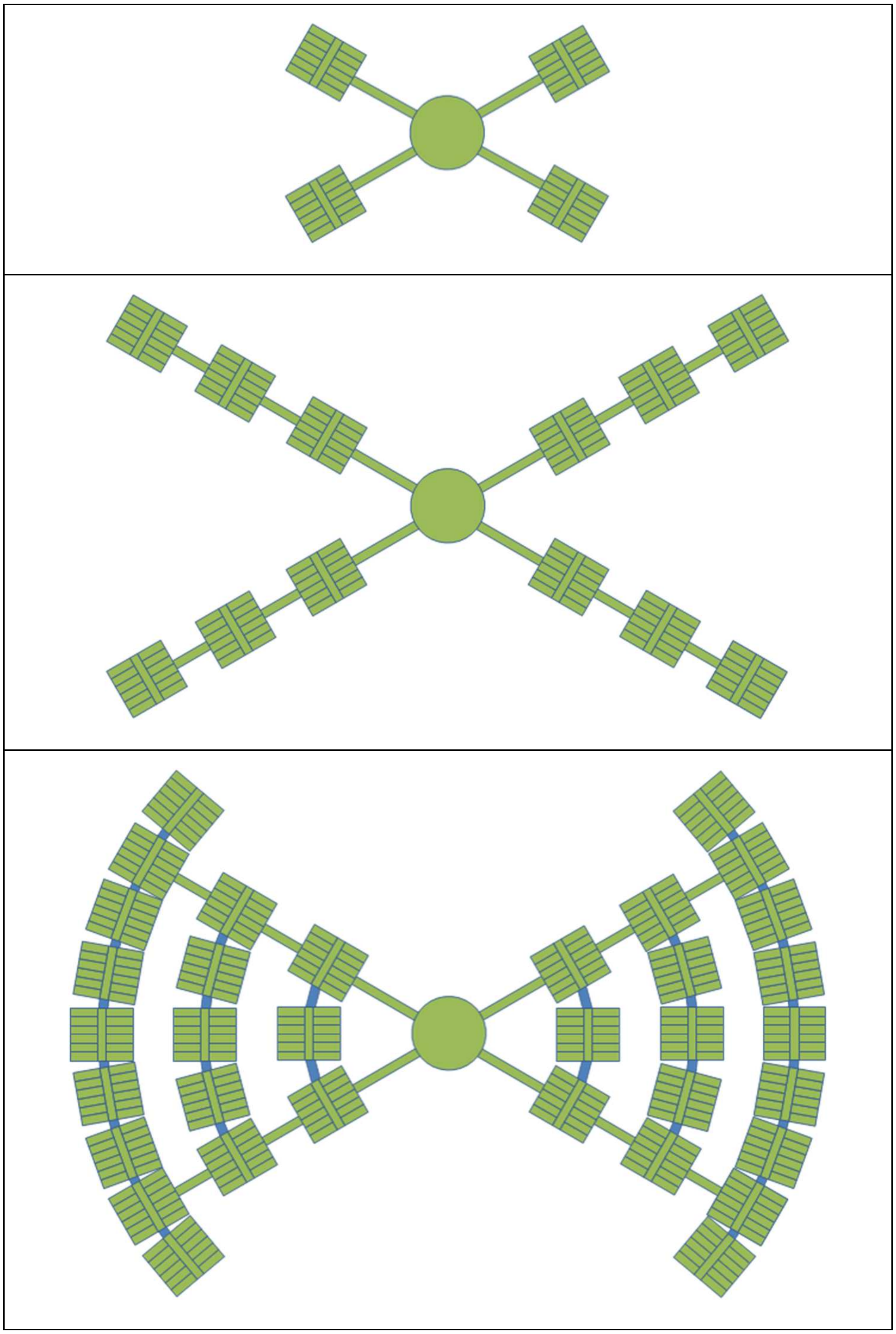


Figure 29: ESHGF Incremental Implementation with 26-Cabin HGVCs in 'X' Configuration Top View Implementations: 4-HGVC (top), 12-HGVC (middle), 34-HGVC (bottom)

The 'X' configuration shown in Figure 29 is a 4-Spoke configuration that has the benefit of being spin-stabilized in all three axes when rotated as is the 'Y' configuration. It also supports a high-density of HGVCs when increased capacity is desired. An 'X' configuration can be created by combining two 'I' configurations when needed. A 6-Spoke configuration can be created by combining a 4-Spoke 'X' configuration with a 2-Spoke 'I' configuration.

3.0 CONCEPT OF OPERATIONS

The ESHGF can be operated in a number of ways (use concepts) as well as operated in different configurations at different development stages. This section concludes with day-in-the-life examples.

3.1 Operation Mode Concepts

The operation mode concepts are summarized in Table 3, each of which is discussed in this section. The operation mode of each HGVC in a HGV can be independently changed during operation to provide needed flexibility.

Operation Mode Description	Rationale	HGV Operation Duration	Human Occupant Duration
Unoccupied short-term operation	- Perform short-term HGV testing - Short-term plant and animal experiments	< 1 day	0
Unoccupied continuous operation	- Long-term HGV testing - Long-term plant and animal experiments	Indefinite	0
Occupied short-term operation	- Evaluate short-term hypergravity effects on humans - Perform tasks requiring humans - Support short-term visitors - Transfer Vehicle not required	< 1 day	< 1 day
Continuous operation with short tours of duty	- Long-term HGV testing - Plant and animal experiments - Evaluate short-term hypergravity effects on humans - Perform short-term treatments on humans - Perform tasks requiring humans - Support short-term visitors	Indefinite	< 1 day
Continuous operation with long tours of duty	- Long-term HGV testing - Plant and animal experiments - Evaluate long-term hypergravity effects on humans - Perform long-term treatments on humans - Perform tasks requiring humans - Support short-term visitors - Artificial-Gravity Space Settlement Analogue	Indefinite	Indefinite

Table 3: Operation Mode Concept Summary

3.1.1 Unoccupied short-term operation mode

The Unoccupied short-term operation mode is expected to be used for testing the HGV in the ESHGF. The HGV may also be tested in this mode on a commercial track.

In the ESHGF, the HGV can be used to characterize the short-term effects of the HGV on objects, animals, and plants prior to a HGV being used by humans.

3.1.2 Unoccupied long-term operation mode

The HGV, or a subset of its HGVCs, can be used to characterize the long-term effects of hypergravity and low-RPM high-radius rotation on objects, manufacturing processes, animals, and plants without requiring the presence of humans, e.g., perform science regarding the multi-generational effects of hypergravity on plants, fish, birds, mammals, etc....

3.1.3 Occupied short-term operation mode

Once the HGV has been tested without humans and certified as safe for human occupancy for short-terms, the HGV can be used to evaluate short-term hypergravity effects on humans.

The HGV can also be used for demonstrating the system capabilities for short-term visitors. High-density population HGVCs may be dedicated for this purpose.

When the entire HGV is operated in this mode, the Transfer Vehicle is not required since the entire HGV can stop at the DCC for loading and unloading.

3.1.4 Continuous operation with short tours of duty mode

A primary purpose of this mode is to study the hypergravity/rotation effect on people such that the tours of duty can be safely extended to indefinite durations.

Assuming that by performing short-term tests on people it is determined that there is a therapeutic benefit for people to undergo hypergravity for short periods, the HGV could be used in this mode to perform such treatments, e.g., strength building, osteoporosis mitigation, and extended microgravity rehabilitation.

This mode also can be used for HGVCs being used for the unoccupied, long-term operation described in 3.1.2, but tasks requiring humans for short-terms are needed, e.g., perform animal examinations and maintenance that can be performed during operation.

Another purpose for this mode is to study the periodic effects of hypergravity on humans. For example, an experiment may characterize any differences in the effects of hypergravity between two groups of people; one group who for 180 days alternates between being onboard the HGV for 7 days then off for 7 days compared with the other group which alternates between being onboard for 12 hours then off for 12 hours each day for the same 180-day period.

3.1.5 Continuous operation with long tours of duty mode

A primary purpose of this mode, supporting long tours of duty, is to characterize the long-term hypergravity/rotation effects on people, animals, and plants to determine if they can live indefinitely in long-radii rotating artificial-gravity facilities as well as to determine if there are long-term benefits to living in a hypergravity environment. If such benefits do exist, then these facilities can be used for therapy.

Also, an HGV in this mode can be used as an analogue to study and experience what life might be like in long-radii rotating artificial-gravity settlements orbiting Earth, on the Moon, on Earth-Mars cycler orbits (McConaghy, Longuski, & Byrnes, 2002), and on Mars and its moons.

3.2 ESHGF Configurations

The extensible, modular design of the ESHGF supports it being operated in a wide variety of configurations in which its capabilities can be incrementally implemented over time. The following configurations are listed in the proposed order of development.

3.2.1 Single-Car Single-Cabin HGV Initial Checkout on Commercial Track

The simplest configuration is a single HGVC with a single cabin that runs on a commercial track. The basic concepts and systems of the HGVC can be tested prior to building the ESHGV track.

3.2.2 Single-Car Single-Cabin HGV on ESHGV Track

The next configuration is to run the single-cabin HGVC on the superelevated circular ESHGV track.

3.2.3 Multi-Car Single-Cabin HGV

This configuration includes all HGVs with multiple single-cabin HGVCs. In the maximum implementation of this configuration, the HGVCs fill the entire circular track and are connected such that the first HGVC in the front of the HGV is connected to its rear HGVC forming a ring of HGVCs.

3.2.4 Multi-Car Single-Cabin HGV with Transfer Vehicle

As the capacity of the HGV increases, implementing a Transfer Vehicle and track in the ESHGF may be warranted. As discussed in section 2.3, a Transfer Vehicle can be used to efficiently transfer people and cargo on and off the HGV without stopping the HGV. Doing so is less disruptive for HGV operations and less costly by reducing the energy and maintenance costs with stopping and starting the entire HGV.

3.2.5 Single-Car Multi-Cabin HGV

Another configuration option to increase capacity is to add modular cabins to a HGVC. A 26-cabin HGVC is discussed and depicted in figures in section 2.8.2. However, a wide variety of multi-cabin HGVC configurations are feasible and can be implemented so that they can be reconfigured and/or upgraded on demand.

Multi-cabin HGVC configurations facilitate larger habitable spaces, shorter point-to-point distances compared to multiple single cabin HGVCs with the same volume, and provide more variation in rotation radii and hypergravity due to cabin points being further from the track gauge center.

A multi-cabin HGVC can also be configured to more closely replicate a potential rim section of an orbiting settlement when being used as a space settlement analogue.

3.2.6 Multi-Car Multi-Cabin HGV

Just as multiple single-cabin HGVCs can be configured as discussed in section 3.2.3, capacity can be increased with multiple multi-cabin HGVCs. It also facilitates both HGVC specialization and the simultaneous operation of different multi-cabin HGVC configurations for comparison.

3.2.7 Multi-Car Multi-Cabin HGV with Transfer Vehicle

The purpose and configuration of a Multi-Cabin HGVC are similar to those of a single-cabin HGVC and Transfer Vehicle as discussed in section 3.2.4 except that the capacity of each HGVC is increased. An example of a 2-Cabin HGVC with a Transfer Vehicle is shown in Figure 21.

3.2.8 Multi-Car Multi-Cabin HGV with Hub & Spokes

Assuming that the benefits of an ESHGV are confirmed using a single-car HGV, a multi-car multi-cabin HGV with a central Hub & Spokes configuration, as described in section 2.8.2, is recommended to increase HGV capacity and its flexibility to continuously transfer people on and off the HGV, as well as to obtain a closer analogue to an orbiting space settlement,. This configuration can be incrementally implemented by operating the ESHGV in some of the configurations described above first.

3.3 ESHGV Use Case Examples

This section describes the operation of an ESHGV with two use case examples.

3.3.1 Short-Term Occupied Mode with Single-Cabin Single-Car HGV

The HGV is sitting on a 30° superelevated track parked next to the DCC. The single HGVC cabin is pivoted at a -30° so that the cabin floor is level. A retractable bridge (similar to an airport jetway) is extended from the DCC to the HGV. The cargo is loaded followed by the loading of the crew and passengers who proceed to their assigned rooms. Once loaded, the HGV door is sealed and the DCC bridge is retracted.

A brief announcement over the intercom informs the passengers that the HGV is embarking and that they will reach the operating hypergravity level of 1.5g's in 10 minutes. Unlike an airplane, at all times the people are free to continue to move about the HGV. The HGV slowly accelerates at a rate that is barely perceptible to the passengers and the HGVC cabin pivot angle also slowly increases and is not perceptible. The passengers eating in the cafe continue dining without taking notice. The beverage glasses resting on the tables give no indication that the entire cabin is tilting as the HGV accelerates. After 10 minutes, the HGV cabin hypergravity is 1.5g's and the cabin pivot angle is now 30°. Combined with the 30° track back angle, the cabin floor angle is 60° with respect to the ground, but it seems level to all onboard. Just after the HGV reaches its operation speed, a passenger in the cafe notes that his glass does feel heavier since it now weighs 50% more as well as his arm. Another passenger notes that she feels like she is wearing armor when she stands up as the passengers begin to adjust to the hypergravity they are experiencing.

After a full day of operation, another announcement over the intercom informs the passengers that the HGV will be stopping in 10 minutes and to prepare to disembark. The HGV slowly begins to decelerate at an imperceptible rate, e.g., $0.07 m/s^2$. Simultaneously, the Cabin also begins to pivot back to -30° also at an imperceptible rate of 0.1° per second such that the Cabin

stops pivoting at the same moment the HGV stops at the DCC. The DCC bridge is extended to the HGV and the passengers and their cargo then disembark as the HGV is prepared for its next tour. As the passengers leave they feel like they are practically floating as their bodies begin to readjust to the lower gravity of Earth.

3.3.2 Multi-Cabin Multi-Car Nominal HGV Operations with a Transfer Vehicle

The HGV is configured and operates like a small cruise ship with office and manufacturing areas to continuously support 200 crew and passengers who live and work there continuously for months along with a stream of daily visitors. In addition, the HGV is configured with life science areas devoted to raising and studying generations of plants and animals subject to hypergravity and rotation. Medical areas are also devoted to ensuring the safety of all onboard as well as studying the hypergravity and rotation effects on the people. All the HGVCs are two Cabins high providing two decks. There are several large openings between these two decks to provide a more spacious atmosphere as well as support having rooms with balconies on the second deck and space for trees to grow from the first deck into the second deck Cabins.

The Transfer Vehicle is scheduled for over 10 trips per day to load and unload people and cargo on the HGV while the HGV speed remains constant. For each trip, the Transfer Vehicle stops at the DCC; people and cargo unload followed by the loading of people and cargo on their way to the HGV. A water tank located in the Transfer Vehicle chassis is also loaded and a sewage tank is unloaded as needed. The Transfer Vehicle disembarks and within 10 minutes it reaches the operational velocity of the HGV and prepares to dock by matching the pivot angle of its cabin to the pivot angle of the HGVC it is docking with. As the Transfer Vehicle extends its forward retractable arm lock and slowly approaches the target HGVC from the rear, the HGVC extends its forward retractable arm lock to lock with the forward retractable arm lock of the approaching Transfer Vehicle. Once the two front arms make contact and lock, the rear retractable arm locks on both vehicles are extended and locked. These locks are designed to secure both cabins to each other while docking, but for safety reasons either vehicle can unilaterally disengage these locks in an emergency. Once both pairs of retractable arm locks are locked, a retractable vestibule is extended from the Transfer Vehicle to the HGVC Cabin and the transfer of people and cargo between the two vehicles begins. In addition, underneath this vestibule pipes are connected and the transfer of water and sewage commences. This docked configuration of a Transfer Vehicle with a single-cabin HGVC is illustrated in Figure 15, Figure 18, and Figure 14.

After 10 minutes, the vehicles prepare to undock. The fluid transfer pipes are disconnected and the retractable vestibule is retracted followed by the unlocking and retraction of the two pairs of retractable arm locks. Once undocked, the Transfer Vehicle decelerates over the next 5 minutes and stops at the DCC where it repeats this process.

4.0 SUMMARY

The design concept for an extensible, modular, Extended-Stay HyperGravity Facility (ESHGF) was presented. The primary purpose of the ESHGF is to produce a flexible suite of precursor facilities suitable for researching the feasibility of extending the permanent presence of life beyond Earth in artificial-gravity settlements. but an ESHGF will provide a variety of other benefits as well. The ESHGF produces an adjustable hypergravity in a 300m diameter rotating environment for people to work and live in along with animals and plants for long-term periods. Two key features of this environment is that the interior of the rotating facility is effectively both motionless and level with respect to its occupants and cargo while the hypergravity is generated.

The design consists of modules that can be assembled and disassembled as needed to be transported, to change system capacity, to change module purposes, and to upgrade/maintain modules while keeping the overall system operational. The modules are sized for transport, including transport by heavy-lift launch vehicles for operation off-Earth.

For this design concept, an incremental implementation approach is recommended starting with a single-car hypergravity vehicle with a 24 x 4 x 4m cabin on a 300m diameter 30° superelevated track as depicted in in Figure 9 capable of a hypergravity range of 1-2g. Additional cars can be added along with adding additional cabins to each car to approach a high-fidelity ground-analogue of a hub-and-spoke space settlement as shown in Figure 24 and Figure 25.

In conclusion, in order to enable long-term human missions off-Earth, the National Academies Institute of Medicine committee recommended for NASA to focus on giving, “increased priority to understanding, mitigating, and communicating to the public the health risks of long-duration missions beyond Earth orbit” and “using more extensively analog environments that already exist and that have yet to be developed;” (Committee on Creating a Vision for Space Medicine During Travel Beyond Earth Orbit, Board on Health Sciences Policy, 2001). Implementing artificial-gravity settlements and understanding their effects on life appear to be crucial for permanently extending life beyond Earth. The International Academy of Astronautics Study Group on artificial gravity recommended that, “the most efficient means of developing an effective flight artificial gravity countermeasure is by appropriate and timely use of ground facilities” (International Academy of Astronautics, 2009). An NRC report on the NASA Space Technology Roadmaps states, “The panel identified Artificial Gravity Evaluation/ Implementation as a game-changing capability that would greatly mitigate many adverse health effects that would otherwise occur during long-duration habitation in transit (or Earth orbit).” (NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space, 2012, p. 195). An ESHGV implemented on Earth is a rational next step for extending the permanent presence of life beyond Earth.

REFERENCES

Amgueddfa Cymru — National Museum Wales. (2008, 12 15). *Richard Trevithick's steam locomotive.* Retrieved from Amgueddfa Cymru — National Museum Wales: http://www.museumwales.ac.uk/rhagor/article/trevithic_loco/

Andrews, J. T. (2009). *Red Cosmos: K E. Tsiolkovskii, Grandfather of Soviet Rocketry.* College Station, TX: Texas A&M University Press.

Antlauf, W., Bernardeau, F. G., & Coates, K. C. (2004, November). Fast Track. *Civil Engineering, 74*(11), pp. 35-43.

Bachelet, E. (1912). *Patent No. 1020942.* U.S. Retrieved from http://pimg-fpiw.uspto.gov/fdd/42/209/010/0.pdf

Bacon, K. W. (1975). *Patent No. 3889605.*

Bacon, K. W., & Morgan, E. O. (1965). *Patent No. 3167024.* USA.

Bonestell, C. von Braun's Space Station. *In (von Braun, 1952).*

Central Japan Railway. (2014, 6 26). *Central Japan Railway Company Annual Report 2014.* Retrieved from Central Japan Railway Company: http://english.jr-central.co.jp/company/ir/annualreport/_pdf/annualreport2014.pdf

Clément, G., & Bukley, A. (Eds.). (2007). *Artificial Gravity.* Hawthorne and New York, CA and NY: Microcosm Press and Springer.

Committee on Creating a Vision for Space Medicine During Travel Beyond Earth Orbit, Board on Health Sciences Policy. (2001). *Safe Passage: Astronaut Care for Exploration.* (J. R. Ball, & C. H. Evans Jr., Eds.) National Academic Press. Retrieved from http://www.nap.edu/catalog/10218.html

Cybercruises.com. (2003, Nov 4). *Mariner of the Seas, the fifth cruise ship in the Voyager-class for Royal Caribbean Cruises was delivered by Kvaerner Masa-Yards*. Retrieved from Cybercruises.com: http://www.cybercruises.com/masethficrshnov03.htm

Darwin, E. (1809). Zoonomia; or the Laws of Organic Life. Boston, MA: Thomas & Andrews.

Davis-Street, J., & Paloski, W. H. (2007). *Artificial Gravity: Will it Preserve Bone Health on Long-Duration Missions?* NASA. Retrieved from http://ntrs.nasa.gov/search.jsp?R=20070028552

Dickinson, H., & Titley, A. (1934). *Richard Trevithick: The Engineer and the Man.* Cambridge: Cambridge University Press.

Ferrari World Abu Dhabi. (2015, 7 24). *Formula Rossa*. Retrieved from Ferrari World Abu Dhabi: http://www.ferrariworldabudhabi.com/en-gb/attractions/formula-rossa.aspx

Gararin Cosmonaut Training Center. (2015, May 15). *Centrifuge*. Retrieved from Gararin Cosmonaut Training Center: http://www.gctc.su/main.php?id=131

Genchi, G. G., Cialdai, F., Monici, M., Mazzolia, B., mattoli, V., & Ciofani, G. (2015). Hypergravity Stimulation Enhances PC12 Neuron-Like Cell Differentation. *BioMed Research International*. Retrieved from http://dx.doi.org/10.1155/2015/748121

Gerathewohl, S. J. (1961). *Zero-G Devices aand Weightlessness Simulators.* Washington, D.C.: National Academy of Sciences - National Research Council.

Guinness World Records. (2015, 6 26). *Fastest maglev train*. Retrieved from Guinness World Records: http://www.guinnessworldrecords.com/world-records/fastest-maglev-train/

Hall, T. W. (1994). *The Architecture of Artificial-Gravity Environments for Long-Duration Space Habitation.* Doctoral Dissertation. Ann Arbor: University of Michigan.

Harsch, V. (2006, February). Centrifuge "Therapy" for Psychiatric Patients in Germany in the Early 1800s. *Aviation, Space, and Environmental Medicine, 77*(2), pp. 157-160.

Hellinger, R., & Mnich, P. (Nov. 2009). Linear Motor-Powered Transportation: History, Present Status, and Future Outlook. *Proceedings of the IEEE. 97*, pp. 1892-1900. IEEE. doi:10.1109/JPROC.2009.2030249

Hoey, R. G. (2010). Physical Problems, Challenges, and Pragmatic Solutions. In R. P. Hallion (Ed.), *NASA's contributions to aeronautics : aerodynamics, structures, propulsion, and controls* (Vol. 1). Washington, DC: NASA. Retrieved from http://www.nasa.gov/pdf/482993main_ContributionsVolume1.pdf

International Academy of Astronautics. (2009). *Study on Artificial Gravity Research to Enable Human Space Exploration.* (L. Young, K. Yajima, & W. Paloski, Eds.) Cologne: DLR Institute of Aerospace Medicine. Retrieved from https://iaaweb.org/iaa/Scientific%20Activity/Study%20Groups/SG%20Commission%202/sg22/sg22finalreportr.pdf

Kable Intelligence Limited. (2015). *Adventure of the Seas, Voyager-Class Cruise Ship*. Retrieved May 10, 2015, from Ship-Technology.com: http://www.ship-technology.com/projects/adventure/

Khedkar, S. B., Kasav, S. M., Jadhav, V. S., Katkade, S. D., & Gunjal, S. U. (2015). Tilting Train Technology. *International Journal of Advanced Technology in Engineering and Science, 3*(1), 1561-1565. Retrieved from http://www.ijates.com/images/short_pdf/1427564986_939.pdf

Kirk, J. (2008, July 14). *Railway Gazette*. Retrieved June 4, 2015, from Fortescue opens the world's heaviest haul railway: http://www.railwaygazette.com/news/single-view/view/fortescue-opens-the-worlds-heaviest-haul-railway.html

Larson, C. A. (1969). *Rotating Space Station Stabilization Criteria for Artificial Gravity.* NASA. Retrieved from http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19690029825.pdf

Life Magazine. (1940, May 20). "Empire Builder" Hill's Grandson Builds a Jounceless Railroad Car. *Life Magazine*, pp. 41-42.

Maidl, B., Schmid, L., Ritz, W., & Herrenknecht, M. (2008). *Hardrock Tunnel Boring Machines.* Berlin: Ernst & Sohn.

MarineLink.com. (2005, Aug 19). *World's Largest Cruise Ship Launched*. Retrieved from MarineLink.com: http://www.marinelink.com/news/article/world-s-largest-cruise-ship-launched/307105.aspx

Matsnev, E. I. (1996). Angular Acceleration. In C. S. Huntoon, V. V. Antipov, & A. I. Grigoriev (Eds.), *Space Biology and Medicine III: Humans in Spaceflight* (Vol. 3, pp. 333-348). AIAA.

McConaghy, T. T., Longuski, J. M., & Byrnes, D. V. (2002). Analysis of a Broad Class of Earth-Mars Cycler Trajectories. *AIAA Astrodynamics Specialist Conference. 1*, pp. 1-10. Monterey: AIAA/AAS.

NASA - American Society for Engineering Education 1975 Summer Faculty Fellowship Program in Engineering Systems Design. (1977). *Space Settlements: A Design Study.* (R. D. Johnson, & C. Holbrow, Eds.) Washington, D.C.: NASA.

NASA. (1977). *AC76-0525.* Retrieved from Torus Sphere Space Colony Concept Illustration: http://ails.arc.nasa.gov/Images/newimages/JPEGs/highres/AC76-0525.jpg

NASA. (2015). *NASA's Journey to Mars: Pioneering Next Steps in Space Exploration.* Washington D.C.: NASA Publications. Retrieved from http://www.nasa.gov/sites/default/files/atoms/files/journey-to-mars-next-steps-20151008_508.pdf

NASA ARC. (2015, May 19). *Ames Research Center 20-G Centrifuge*. Retrieved from Space Biosciences: http://www.nasa.gov/ames/research/space-biosciences/20-g-centrifuge

National Academies National Research Council Aeronautics and Space Engineering Board. (2012). *NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space.* Washington, D.C.: The National Academies Press.

Oyama, J., & Platt, W. T. (1965). Effects of prolonged centrifugation on growth and organ development of rats. *The American Journal of physiology*, 611-615.

Persson, R. (2007). *Tilting trains: Description and analysis of the present situation Literature study.* Linkoping: Swedish National Road and Transport Research Institute (VTI). Retrieved from http://www.vti.se/en/publications/pdf/tilting-trains--description-and-analysis-of-the-present-situation-a-literature-study.pdf

Post, R. F. (1998). *Patent No. 5722326.* U.S. Retrieved from http://pimg-fpiw.uspto.gov/fdd/26/223/057/0.pdf

Post, R. F., & Ryutov, D. D. (2000). Thc Inductrack: A Simpler Approach to Magnetic Levitation. *IEEB Transactions on Applied Superconductivity. 10(1)*, pp. 901-904. IEEE. doi:10.1109/77.828377

Powell, J. R., & Danby, G. T. (1969). *Patent No. 3470828.* U.S. Retrieved from http://pimg-fpiw.uspto.gov/fdd/28/708/034/0.pdf

Powell, J. R., Maise, G., Paniagua, J., & Rather, J. D. (2001). StarTram: A New Approach for Low-Cost Earth-to-Orbit Transport. *IEEE Aerospace Conference Procs. 5*, pp. 2569-2591. Big Sky, MT: IEEE. doi:10.1109/AERO.2001.931219

Powell, J., Maise, G., & Pellegrino, C. (2013). *StarTram: The New Race to Space.* CreateSpace Independent Publishing.

Reynolds, R. R. (1999). In *Roller Coasters, Flumes and Flying Saucers.* Northern Lights Pub.

Royal Carribean International. (2015, June 4). *Adventure of the Seas*. Retrieved from Royal Carribean International: http://www.royalcaribbean.com/findacruise/ships/class/ship/home.do?shipCode=AD

Sanyal, A. K., Shen, J., McClamroch, N. H., & Bloch, A. M. (2005, September-October). Stability and Stabilization of Relative Equilibria of Dumbbell Bodies in Central Gravity. *Journal of Guidance, Control, and Dynamics, 28*(5), 833-842. doi:10.2514/1.10546

Schoepf, T. H., & Ritchie, D. M. (1937). *Patent No. 2,088,487.* USA.

Schoepf, T. H., & Ritchie, D. M. (1937a). *Patent No. 2,095,677.* USA.

Siemens AG. (2015, July 25). *Amtrak Cities Sprinter ACS-64 Electric Locomotive.* Retrieved from Siemens Locomotives: sitecollectiondocuments/en/rail-solutions/locomotives/customspecific-solutions/amtrak-acs64-en.pdf

The Shanghai Maglev Train. (2015, 6 26). Retrieved from Shanghai China Tourist Information and Travel Guide: http://shanghaichina.ca/video/maglevtrain.html

Trauthwein, G. (2003, February). Navigator of the Seas -- A New Course for Profitability. *Maritime Reporter and Engineering News*, pp. 24-27. Retrieved from http://magazines.marinelink.com/magazines/MaritimeReporter/200302/pdf/

Tsiolkovsky, K. (1895/1979). Dreams of Earth and Sky. Originally published as Grezy o Zemle i nebe i effekty vsemirnogo tjatotenija, (Moscow: A N Gončarov, 1895). In A. Starchild (Ed.), *The Science Fiction of Konstantin Tsiolkovsky* (pp. 52-154). Honolulu, Hawaii: University Press of the Pacific.

Tsiolkovsky, K. E. (1911-1912/2004). Investigation of World Space by Reactive Vehicles (orginally published as Issledovanie mirovykh prostranstv reaktivnymi priborami in Vestnik Vozdukhoplavaniva, 1911-1912). In V. N. Sokolsky, & A. A. Blagonravov (Eds.), *Selected Works of Konstantin E. Tsiolkovsky* (G. Yankovsky, Trans., Second ed., pp. 83-139). Honolulu, Hawaii: University Press of the Pacific.

U.S. Federal Government. (2011). *Code of Federal Regulations Title 46* (Vols. 4, Part 115-114). Washington, D.C.: U.S. Government Printing Office. Retrieved from http://www.gpo.gov/fdsys/pkg/CFR-2011-title46-vol4/pdf/CFR-2011-title46-vol4-part115.pdf

Van Dorn, W. E., & Beemer, P. K. (1940). *Patent No. 2,225,242.* USA. Retrieved from http://pimg-fpiw.uspto.gov/fdd/42/252/022/0.pdf

van Loon, J. J. (2009, January). The Human Centrifuge. *Microgravity Science and Technology, 21*(1-2), 203-207. doi:10.1007/s12217-008-9062-z

van Loon, J. J. (2012). A large human centrifuge for exploration and exploitation research. *Annales Kinesiologiae, 3*(1), 107-121. Retrieved from http://ojs.zrs.upr.si/index.php/AK/article/view/67

van Loon, J. J., & Wuyts, F. (2009). The Large Radius Human Centrifuge 'A Human Hypergravity Habitat, H3'. *60th International Astronautical Congress Space Life Sciences Symposium.* Seoul, Korea: International Astronautical Federation.

von Braun, W. (1952, March 22). Crossing the Last Frontier. *Collier's*, pp. 24-30, 72-74.

Yang, Y., Baker, M., Graf, S., Larson, J., & Caiozzo, V. J. (2007). Hypergravity resistance exercise: the use of artificial gravity as potential countermeasure to microgravity. *J Appl Physiol, 103*, 1879-1887. doi:10.1152/japplphysiol.00772.2007

Zehden, A. (1905). *Patent No. 782312.* U.S. Retrieved from United States Patent and Trademark Office: http://pimg-fpiw.uspto.gov/fdd/12/823/007/0.pdf

Zhao, J. (2012). *A General Overview on Tunnel Boring Machines.* Society for Rock Mechanics & Engineering Geology Seminar. Singapore: Nanyang Technological University. Retrieved from http://www.ncus.ntu.edu.sg/Events/Documents/SRMEG%20Seminar%20Tunnel%20Boring%20Machines.pdf

APPENDIX A: ABBREVIATIONS AND ACRONYMS

Define all abbreviations and acronyms that are not defined in a standard dictionary.

Acronym	**Definition**
cm	centimeter
DCC	Depot / Control Center
ESA	European Space Agency
ESHGF	Extended-Stay HyperGravity Facility
g	Gravity-level at surface of Earth in (m/s^2)
h	Hour
HGV	HyperGravity Vehicle
HGVC	HyperGravity Vehicle Car
kg	Kilogram
LEO	Low Earth Orbit
m	Meters
m	Miles Per Hour
NRC	National Research Council
RPM	Revolutions Per Minute
s	Seconds

APPENDIX B: HGVC METRICS

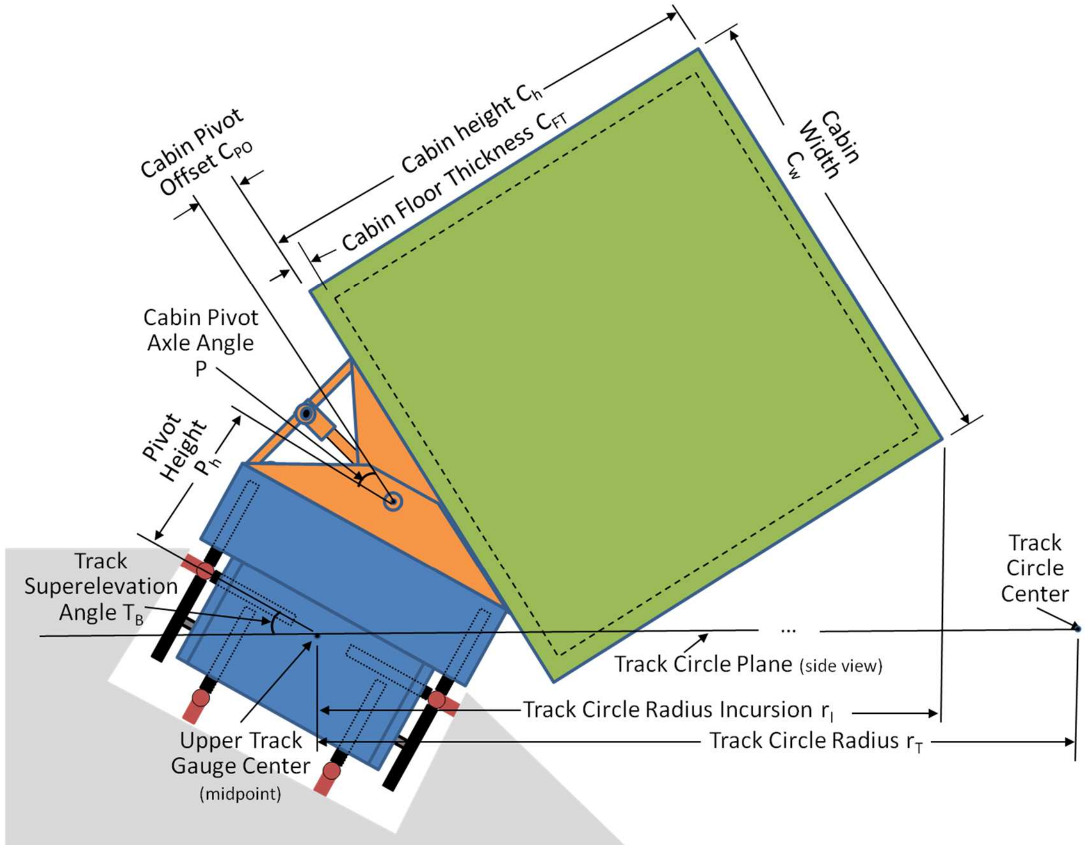


Figure 30: HGVC Tilted Cabin on Track – Rear View

As defined in Equation 1, the hypergravity is a function of the distance of each cabin point relative to the track circle center. One of the parameters required is the distance from the HGVC cabin point to the center of the track circle. This distance, e.g., radius for a given cabin floor point (x, y, C_{FT}) coordinate at Cabin Pivot angle P, is defined by Equation 4 (the HGVC Cabin coordinate frame is defined in section 2.6.1 and depicted in Figure 20).

$$r_{pos}(x, y, z, P) = \sqrt{x^2 + (r_T + r_B + r_{CO} + r_P(y, z, P))^2}$$

Equation 4: Cabin Point Radius at cabin coordinates (x, y, z) at Pivot Angle P (m)

Superelevating the track by angle T_B has the effect of shifting the cabin pivot-axle centerline toward the track center by r_B per Equation 5.

$$r_B = -\sin(T_B \cdot \pi/180) \cdot P_h$$

Equation 5: Track Superelevation (Bank) Angle Radius Offset (m)

Similarly, pivoting the Cabin by angle P, in addition to the track superelevation angle T_B, also has the effect of shifting cabin point radii. The radii of the cabin points in the vertical plane where x=0 are offset by $r_P(y, z, P)$ per Equation 6.

$$r_P(y,z,P) = -\cos\left(\cos^{-1}\left(\frac{-y}{\sqrt{y^2 + (C_{PO} + z)^2}}\right) - (P + T_B)\ \cdot\ \pi/180\right) \cdot \sqrt{y^2 + (C_{PO} + z)^2}$$

Equation 6: Cabin Pivot Angle Radius Offset at Cabin Pivot Angle P at height z (m)

Note that when the Cabin Pivot angle offsets the Track Superelevation angle such that the Cabin is level, the Cabin Pivot Angle Radius Offset is y, i.e., $r_P(y, z, -T_B) = y$.

Since the track is curved but the Cabin is straight, the center of the Cabin, (0,0,0), is off the track circle by an additional offset of r_{CO} per Equation 7.

$$r_{CO} = \sqrt{r_T^2 - \left(\frac{C_L}{2} - W_{TO}\right)^2} - r_T$$

Equation 7: Chassis Centerline Center Offset at point equidistant between truck centers (m)

where (see Figure 13 and Figure 30):
r_T = Track Radius (m)
T_B = Track Superelevation (Bank) Angle (degrees)
P_h = Pivot Axle Height (distance from track base between upper rails to Pivot Axle Center) (m)
C_{PO} = Cabin Pivot Offset (distance from Pivot Axle Center to Cabin bottom) (m)
P = Cabin Pivot Axle Angle (degrees)
C_L = Cabin Length (m)
C_W = Cabin Width (m)
W_{TO} = Car Wheel Truck Offset (distance from cabin end to nearby chassis truck center) (m)
(Same distance for front and rear trucks for attaching HGVCs to each other.)
x = Cabin length position (distance between cabin floor coordinates ($-C_L/2$, 0) and ($C_L/2$, 0) (m)
y = Cabin width position (distance between cabin floor coordinates (0, $-C_W/2$) and (0, $C_W/2$) (m)

As per Equation 4, the radius from the track circle center to a point at coordinates (x, y) on a cabin floor is the track circle radius that is offset by the effect of the track superelevation angle, the cabin pivot angle, the chassis centerline center offset, and the cabin floor position (x, y) offsets.

The track superelevation angle radius offset, Equation 5, is zero when the superelevation angle is zero, but is equal to the Pivot axle center height, when the superelevation angle = 90° as would be the case in a micro gravity environment, see Figure 30.

Similarly, the pivot angle radius offset, Equation 6, is zero when the pivot angle is equal to the negative of the track superelevation angle (when the HGV is stopped, see Figure 19). In the case when the sum of the track superelevation angle and the cabin pivot angle is 90°, i.e., when the cabin floor is perpendicular to the track circle plane, the pivot angle radius offset is equal to the

cabin floor height from the pivot axle, see Figure 30. For a “second-story cabin,” this height is increased by the height of the first-story cabin. The hypergravity in the second story cabin decreases accordingly.

The chassis centerline center offset is due to the chassis and cabin being straight lengthwise and not being arced at same radius as the track. Consequently, the chassis lengthwise centerline forms a chord intersecting the track circle as illustrated in Figure 13, where the each truck center-point is the track radius from the track circle center. The chassis centerline offset is essentially the chord height measured midway between the chassis truck centers.

APPENDIX C: HGVC TRACK CAPACITY

The maximum number of HGVCs that can fit on a circular track is a function of the track radius, the maximum track-circle incursion distance, the HGVC length at this distance, and the minimum cabin spacing margin, C_{sm}, between HGVCs (to avoid collisions between the top inner rear corner of a cabin on an HGVC and the top inner front corner of a cabin on the immediately following HGVC as shown in Figure 14) when pivoting the cabins. The problem is essentially to maximize n for an n-gon:

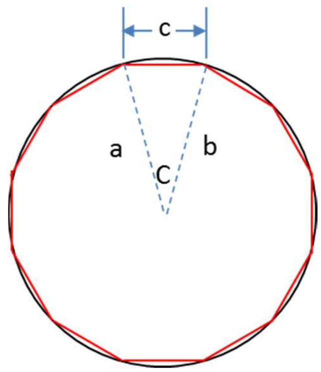


Figure 31: Maximum Dodecagon in a Circle

Figure 31 depicts a Dodecagon (12-sided n-gon) with its vertices on a circle. The length of each side c, with both vertices on the circle, can be calculated using the law of cosines, $c^2 = a^2 + b^2 - 2ab\,cos(C)$. This equation is restated in Equation 8.

$$c = \mathrm{r}\sqrt{2 - 2\cos\left(\frac{2\pi}{n}\right)}$$

Equation 8: n-gon side length

where:
c = Length of each side of a n-gon (m)
n = number of sides of the circumscribed n-gon, where C = 2π/n
r = Circle radius (m)

By substitution and maximizing n, Equation 8 is reformulated as Equation 9.

$$n_{mx} = trunc\left(\frac{2\pi}{\cos^{-1}\left(1 - \frac{(C_{TL} + C_{Lm})^2}{2(r_T - r_I)^2}\right)}\right)$$

Equation 9: Maximum number of HGVCs

where:
n_{mx} = the maximum number of n-gon sides, each which represents an HGVC Cabin top inside edge
C_{TL} = the total HGVC Cabin inside edge length for all cabins on the HGVC (m)
C_{Lm} = the minimum Cabin length margin between top inner cabin corners of adjacent HGVCs, i.e., the length the cabins can be increased without colliding when pivoted (m)
r_T = Track Circle Radius (m)
r_I = maximum radius corner incursion offset of an HGVC Cabin defined by Equation 11

The maximum radius corner incursion offset of an HGVC Cabin, r_I, occurs when the Cabin is tilted such that the height of the upper inner Cabin Edge are the same height as the Cabin Pivot Axle center, which occurs at the Cabin Pivot Angle P_{Imx} and is defined by Equation 10.

$$P_{Imx} = \tan^{-1}\left(\frac{2(C_{TH} + C_{PO})}{C_{TW}}\right) \cdot \frac{180}{\pi} - T_B$$

Equation 10: HGVC Cabin Pivot Angle that maximizes top inner edge incursion

where:
C_{TH} = Cabin Total Height (total Cabin Height of all Cabin Stories)
C_{TW} = Cabin Total Width (total includes any Cabins adjacent to the center Cabin)
C_{PO} = Cabin Pivot Offset (distance from Pivot Axle Center to Cabin bottom) (m)
T_B = Track Superelevation (Bank) Angle (degrees)

The maximum radius corner incursion offset, r_I, is defined by a special case of the Cabin Point Radius equation (Equation 4) where the point is a Cabin roof inner corner (assuming the Cabin is centered on the Chassis) and the Cabin Pivot angle P = P_{Imx}, and is parameterized in Equation 11.

$$r_I = r_T - r_{pos}(C_{TL}/2,\ C_{TW}/2,\ C_{TH} + C_{PO},\ P_{Imx})$$

Equation 11 : HGVC Cabin Maximum Radius Corner Incursion Offset (m)

Once n_{mx} is determined, the actual minimum cabin distance (spacing margin) between top inner cabin corners of adjacent HGVCs , C_{sm}, can be determined by Equation 12.

$$C_{sm} = \left((\mathrm{r_T} - r_I)\sqrt{2 - 2\cos\left(\frac{2\pi}{n_{mx}}\right)} - C_{TL} \right) \cdot \sin\left(\frac{(n_{mx} - 2)\pi}{2n_{mx}}\right)$$

Equation 12: Minimum Inter-HGVC Cabin Spacing (between top inner corners)

Consider the following example. For the multi-cabin HGVC shown in Figure 23 with each Cabin 4m high, 4m wide, and the side Cabins 12m long, C_{TH} = 2·4=8m, and C_{TW} = 4 + 2·12=28m. For a 300m diameter track with a superelevation angle, T_B=30°, a Pivot Axle height of P_h=3.4m, and a Cabin Pivot Offset C_{PO} = 1.5m, the Pivot Angle that maximizes the Cabin incursion into the

track circle is P_{Imx} = 4.16° per Equation 10 and the maximum radius corner incursion offset is r_I = 18.3m per Equation 11, but for a 4x4x24m single-cabin HGVC, P_{Imx} = 36° and the incursion offset r_I = 5.2m. Consequently per Equation 9, with a minimum Cabin length margin C_{Lm}= 0.25m, the maximum number of multi-cabin HGVCs that will fit on the track is n_{mx} = 34, with a Cabin spacing minimum of C_{sm} = 29cm per Equation 12. Similarly the maximum number of the single-cabin HGVCs on a 300m dia. track is n_{mx} = 37 with a Cabin spacing minimum of C_{sm} = 56cm.

In the above example, only 34 of the specified multi-cabin HGVCs will fit on a 300m dia. track. If the system is designed such that $P_{Imx} + T_B = 90°$, that is the HGVCs Cabins are always perpendicular to the rotation plane as would be the case on-orbit and on low-gravity bodies like the Moon, 36 HGVCs would fit in a 300m diameter circle. On Earth, 36 of the same size HGVCs require a 315m track diameter, i.e., r_T = 157.5m, per Equation 9, due to the maximum cabin incursion offset of 18.36m per Equation 11. This 36-HGVC configuration is described in section 2.8.3 ESHGF Hub-and-Spoke Subsystem Architecture.